Final Draft

AC/AMJ 20-TBD

AIRCRAFT LIGHTNING ENVIRONMENT AND RELATED TEST WAVEFORMS

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1.0 PURPOSE

This Advisory Circular/Advisory Material Joint (AC/AMJ) is one of the set of three documents covering the whole spectrum of aircraft interaction with lightning. The purpose of this AC/AMJ is to provide the characteristics of lightning that are encountered by aircraft as well as transients appearing at the interfaces of equipment associated with electrical/electronic systems as a result of that interaction. These characteristics are referred to as the aircraft lightning environment. The two other documents provide advisory material on aircraft lightning zoning (Reference 4.1) and aircraft lightning testing (Reference 4.2), and are hereinafter referred to as the Zoning AC/AMJ and the Testing Standard. The relationship between the three documents is shown in Figure 1-1.

2.0 SCOPE

The environment and test waveforms defined in this AC/AMJ account for the best lightning data and analysis currently available. The quantified environment and levels herein represent the minimum currently required by certifying authorities, consistent with the approach applied in related lightning documents.

Lightning, like any natural phenomenon, is probabilistic in nature. Levels and waveforms vary considerably from one flash to the next. These standardized voltage and current waveforms have been derived to represent the lightning environment, and are used to assess the direct effects of lightning on aircraft. The standardized external current waveforms have in turn been used to derive standardized transient voltage and current waveforms which can be expected to appear on the cable bundles and at equipment interfaces.

In addition, test waveforms based on current industry best practice are included to supplement these waveforms that are derived directly from the lightning environment. Considerations such as testability and important waveform characteristics that can demonstrate lightning design effectiveness are taken into account.

The parameters of the standardized waveforms, both external and derived transients, represent severe versions of each of the characteristics of natural lightning flashes and include all parameters of interest with respect to lightning protection for aircraft. However, it should be noted that in every case more severe versions of each of the characteristics of the standardized waveforms have been recorded in natural lightning flashes as well as additional parameters such as electric field effects in non-conductive structures.

The test waveforms provided in this AC/AMJ are considered to be adequate for the demonstration of compliance for the protection of an aircraft and its systems against the lightning environment and should be applied in accordance with the aircraft lightning strike zones (Reference 4.1) and test methods (Reference 4.2), and applicable FAA and JAA advisory and interpretive material.
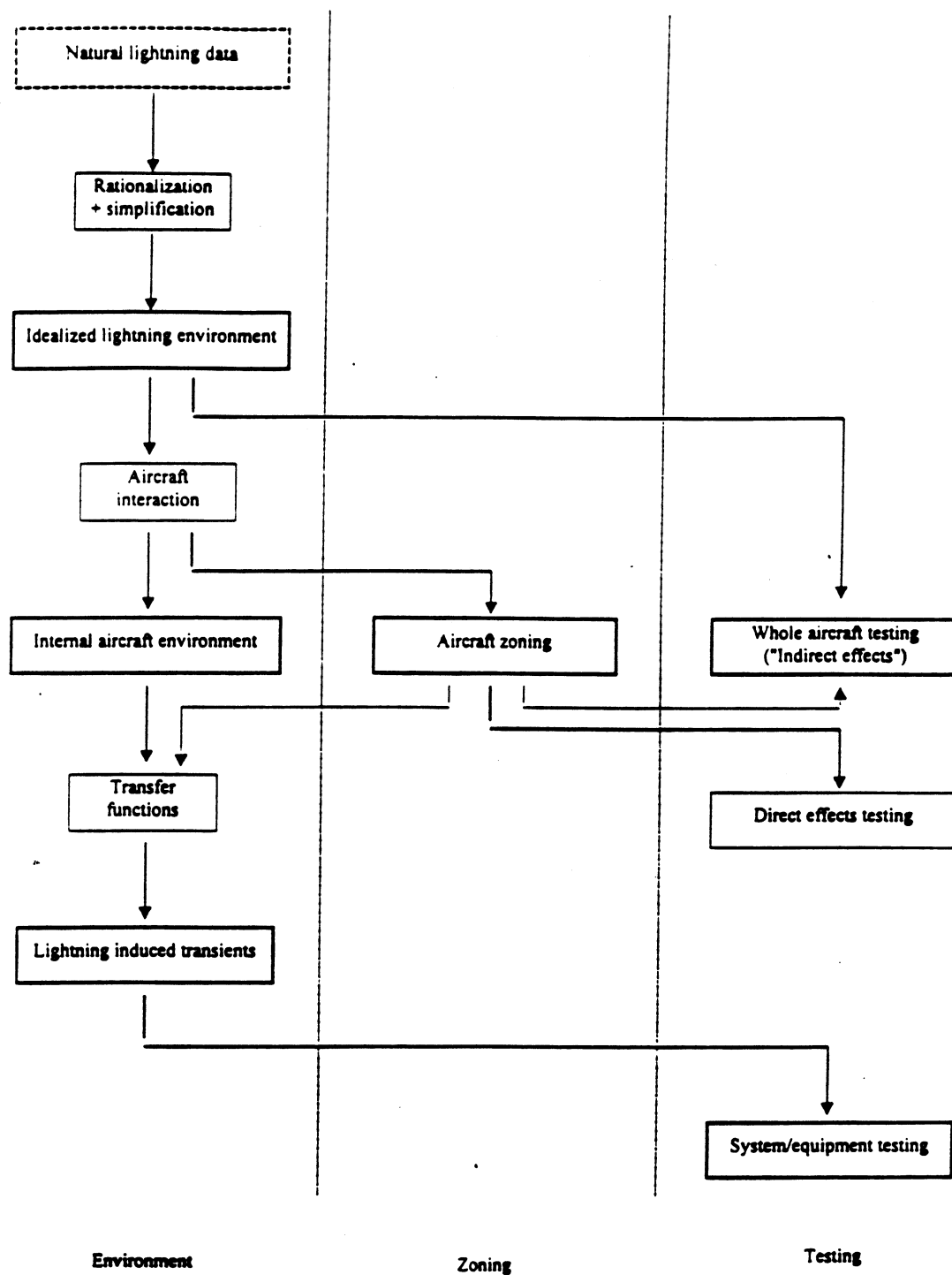
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Figure 1-1. Relationship between aircraft environment, zoning and testing

Note: Solid lines represent the actual AC/AMJ and Standard's materials and processes addressed in the documents. The dotted lines represent the supporting materials and processes.

3.0   RELATED FAR AND JAR INFORMATION

3.1   Federal Aviation Regulations (FAR).

Federal Aviation Regulations 14 CFR Parts 23.867, 23.954, 23.1309(e), 23.1316, 25.581, 25.954, 25.1316, 27.610, 27.954, 27.1309(d), 27.1316, 29.610, 29.954, 29.1309(h), 29.1316 and 33.28(d).

3.2   FAA Advisory Circulars.

The following Advisory Circulars (AC) may provide additional information.

3.2.1   AC 23.1309-1B, System and Equipment Installations in Part 23 Airplanes, dated July 28, 1995.

3.2.2   AC 25.1309-1A, System Design and Analysis, dated June 21, 1988.

3.2.3   AC 27-1, Certification of Normal Category Rotorcraft, dated August 8, 1985, including to Change 4 dated August 18, 1995.

3.2.4   AC 29-2A, Certification of Transport Category Rotorcraft, dated September 16, 1987, including to Change 3 dated June 1, 1995.

3.2.5   AC 21-16D, Radio Technical Commission for Aeronautics Document DO-160D, dated March, 1998.

3.3   Joint Airworthiness Requirements (JAR).

Joint Airworthiness Requirements Parts 23.867, 23.954, 23.1309(e), 23.1316, 25.581, 25X899, 25.954, 25.1316, 27.610, 27.954, 27.1309(d), 27.1316, 29.610, 29.954, 29.1309(h), 29.1316, 33.28(d) and JAR E.50.

3.4   JAA Advisory and Interpretive Material.

3.4.1   ACJ 25X899, Electrical Bonding and Protection Against Lightning and Static Electricity (Interpretive Material and Acceptable Means of Compliance).

3.4.2   ACJ 29.610, Lightning and Static Electricity Protection (Interpretive Material and Acceptable Means of Compliance).

3.4.3   AMJ 20X-1, Certification of Aircraft Propulsion Systems Equipped with Electronic Controls.

4.0   REFERENCE DOCUMENTS

4.1   AC/AMJ 20-TBD (in preparation)
"Aircraft Lightning Zoning "

4.2   EUROCAE WG 31/SAE AE4L document APR-TBD (in preparation)
"Aircraft Lightning Testing Standard"

4.3   EUROCAE ED-14D/RTCA DO-160D
"Environmental Conditions and Test Procedures for Airborne Equipment"
Section 22: "Lightning Induced Transient Susceptibility"

4.4   EUROCAE ED-14D/RTCA DO-160D
"Environmental Conditions and Test Procedures for Airborne Equipment"
Section 23: "Lightning Direct Effects"

4.5   AC/AMJ 20-136A
"Protection of Aircraft Electrical/Electronic Systems against the Indirect
Effects of Lightning"

4.6   AC/AMJ 20-53B
"Protection of Airplane Fuel Systems Against Fuel Vapor Ignition Due to
Lightning"

4.7   User's Guide for SAE AE4L Committee Report AE4L-87-3 Revision C
EUROCAE WG 31/SAE AE4L document (in preparation).

5.0   BACKGROUND

The environment information and the test waveforms have been removed from AC/AMJ 20-136 and AC/AMJ 20-53, and included in this AC/AMJ. This AC/AMJ also explains the idealized external waveforms and gives a brief discussion of the mechanisms for transforming the external environment into an internal environment and the resulting transients on cable bundles and at equipment interfaces.

6.0 DEFINITIONS/ABBREVIATIONS/ACRONYMS

6.1 Definitions

Action Integral	The integral of the square of the time varying current over its time duration. It is usually expressed in units of ampere squared seconds (A^2s).
Aperture	An electromagnetically transparent opening.
Aperture Coupling	The process of inducing voltages or currents in avionics wiring or systems by electric or magnetic fields passing through apertures.
Attachment Point	A point of contact of the lightning flash with the aircraft.
Breakdown	The production of a conductive ionized channel in a dielectric medium resulting in the collapse of a high electric field.
Cable Bundle	A group of wires and/or cables bound or routed together that connect two pieces of equipment.
Charge Transfer	The time integral of the current over its entire duration, in units of coulombs ($A \times s$).
Continuing Current	A low level long duration lightning current that occurs between or after the high current strokes.
Dart Leader	A leader which occurs before subsequent strokes without stepping but with a continuous progression of the leader tip.
Diffusion	The process by which electric current flow spreads through the thickness of a conductive material which results in a slower increase in current density on interior surfaces as compared with exterior surfaces.
Direct Effects	Any physical effects to the aircraft and/or equipment due to the direct attachment of the lightning channel and/or conduction of lightning current. This includes dielectric puncture, blasting, bending, melting, burning and vaporization of aircraft or equipment surfaces and structures. It also includes directly injected voltages and currents in associated wiring, plumbing, and other conductive components.
Dwell Time	The time that the lightning channel remains attached to a single spot on the aircraft.

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Equipment Interface	A location on an equipment boundary where connection is made to the other components of the system of which it is part. It may be an individual wire connection to an electrical/electronic item, or wire bundles that interconnect equipment. It is at the equipment interface that the equipment transient design level (ETDL) and transient control level (TCL) are defined and where the actual transient level (ATL) should be identified.
External Environment	Characterization of the natural lightning environment for design and certification purposes.
First Return Stroke	The high current surge that occurs when the leader completes the connection between the two charge centers. The current surge has a high peak current, high rate of change of current with respect to time (di/dt) and a high action integral.
Flashover	This term is used when the arc produced by a gap breakdown passes over or close to a dielectric surface without puncture.
Indirect Effects	Electrical transients induced by lightning in aircraft conductive components such as electric circuits.
Induced Voltages	A voltage produced in a circuit by changing magnetic or electric fields or structural IR voltages.
Interface Transients	Induced voltages and currents appearing in cable bundles or in individual conductors, and which appear at equipment interfaces.
Internal Environment	The fields and structural IR voltages inside the aircraft produced by the external environment.
K Changes	Electric (E) field changes and current pulses seen inside the cloud during cloud to ground flashes and often associated with current pulses.
Leader	The low luminosity, low current precursor of a lightning return stroke, accompanied by an intense electric field.
Lightning Channel	The ionized path through the air along which the lightning current pulse passes.
Lightning Flash	The total lightning event. It may occur within a cloud, between clouds or between a cloud and ground. It can consist of one or more return strokes, plus intermediate or continuing currents.

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Lightning Strike	Any attachment of the lightning flash to the aircraft.
Lightning Strike Zones	Aircraft surface areas and structures classified according to the possibility of lightning attachment, dwell time and current conduction. (See the Zoning Adversary Circular.)
Multiple Burst	Randomly spaced groups of short duration, low amplitude current pulses, with each pulse characterized by rapidly changing currents (i.e. high di/dt's). These pulses may result from lightning leader progression or branching. The pulses appear to be most intense at the time of initial leader attachment to the aircraft.
Multiple Strike	Two or more lightning strikes during a single flight.
Multiple Stroke	Two or more lightning return strokes occurring during a single lightning flash.
Peak Rate of Rise	The maximum value of the derivative with respect to time of i(t) and may be expressed as follows: Peak rate of rise = maximum of di(t)/dt
Recoil Streamer	Equivalent to restrike during a cloud to cloud or intra cloud discharge and associated with isolated current pulses.
Restrike	A subsequent high current surge attachment, which has a lower peak current, a lower action integral, but a higher di/dt than the first return stroke. This normally follows the same path as the first return stroke, but may reattach to a new location further aft on the aircraft.
Shield	A conductor which is grounded to an equipment case or aircraft structure at both ends and is routed in parallel with and bound within a cable bundle. It usually is a wire braid around some of the wires or cables in the cable bundle or may be a metallic conduit, channel or wire grounded at both ends within the cable bundle. The effect of the shield is to provide a low impedance path between equipment to be connected.
Slow Components	The intermediate current and the continuing current collectively.
Stepped Leader	See leader.

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<u>Structural IR Voltage</u>	The structural IR voltage is the portion of the induced voltage resulting from the product of the distributed current (I) and the resistance R of the aircraft skin or structure.
<u>Swept Channel</u>	The lightning channel relative to the aircraft, which results in a series of successive attachments due to sweeping of the flash across the aircraft by the motion of the aircraft.
<u>Swept Leader</u>	A lightning leader that has moved its position relative to an aircraft, subsequent to initial leader attachment, and prior to the first return stroke arrival, by virtue of aircraft movement during leader propagation.
<u>System Functional Upset</u>	An impairment of system operation, either permanent or momentary (e.g., a change of digital or analog state) which may or may not require manual reset.
<u>Upset</u>	See system functional upset.
<u>V</u>90	This is normally the voltage to which an HV impulse generator must be erected in order that 90% of all discharges will result in gap breakdown.
<u>Zoning</u>	The process (or the end result of the process) of determining the location on an aircraft to which the components of the external environment are applied.

6.2 Abbreviations

kV	kilovolts
kV/m	kilovolts per meter
A	amperes
m/s	meters per second
μs	microseconds
s	seconds
ms	milliseconds
kA	kiloamperes
t	time
C	charge transfer (coulombs or ampere - seconds)
A/s	amperes per second
A^2s	action integral (ampere squared seconds)

6.3 Acronyms

ETDL	Equipment Transient Design Level
FWHM	Full Width Half Maximum: The time interval between 50% amplitudes of a pulse.
HC	High current.
HV	High voltage.
LRU	Line replaceable unit: An element of a system which may be removed and replaced by a line maintenance crew while the aircraft is in operational status.
MB	Multiple Burst
MS	Multiple Stroke
N/A	Not Applicable
TCL	Transient Control Level

7.0   NATURAL LIGHTNING DESCRIPTION

7.1   General

Lightning flashes usually originate from charge centers in a cloud, particularly the cumulonimbus cloud, although they can occur in other atmospheric conditions. The charges in clouds are produced by complex processes of freezing and melting and by movements of raindrops and ice crystals involving collisions and splintering. Typically, most positive charges accumulate at the top of the cumulonimbus clouds, leaving the lower regions negative, although there may be a small positive region near the base. The result is the typical structure of Figure 7-1 depicted by Malan (Reference 7.5.1), who extensively studied thunderstorms in South Africa.

During their process of development thunder clouds extend vertically over more than 3 km. The strong electric fields can initiate discharges, called lightning flashes, which may be of three types, namely:

a) Flashes between regions of opposite polarity within a cloud (intra cloud discharges),
b) Flashes between regions of opposite polarity in different clouds (inter cloud charges), and,
c) Flashes from clouds to ground and from ground to clouds of either polarity. Ground to cloud flashes, however, become only relevant to taller objects, e.g. towers and mountains.

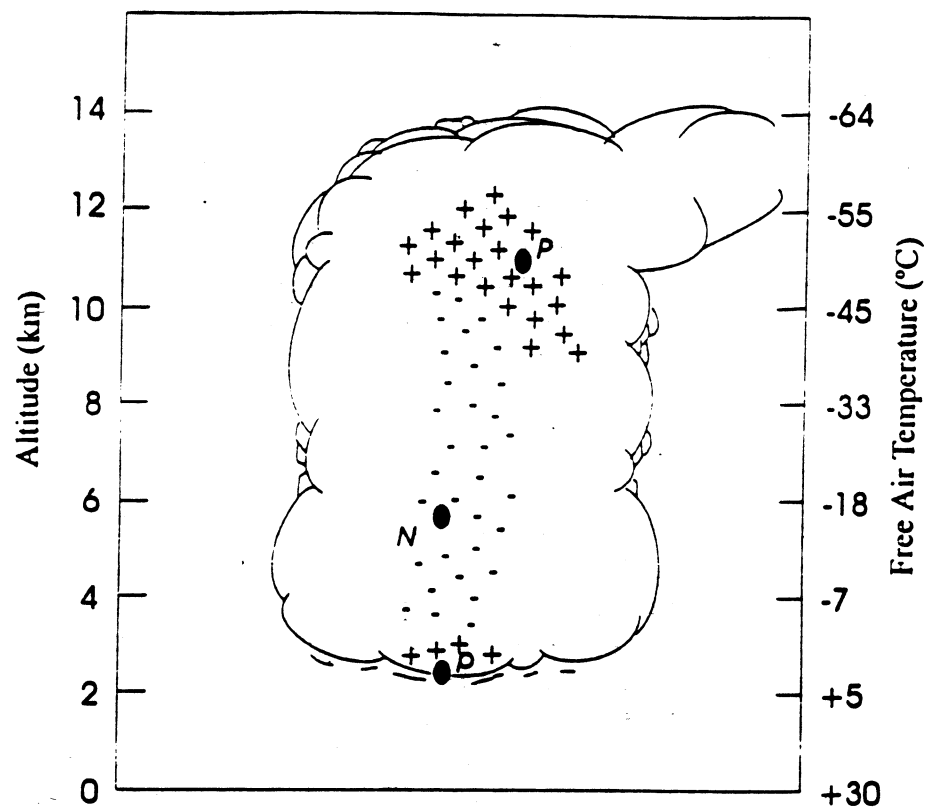Over 50% of all flashes are intra cloud flashes.

Figure 7-1. Generalized diagram showing distribution of air currents and electrical charge in typical cumulonimbus cloud.

7.2 Cloud-to-Ground Flashes

7.2.1 The discharge process

A positive flash lowers positive charge to earth while a negative flash lowers negative charge.

It is common for a negative flash to discharge several charge centers in succession, with the result that the flash contains several distinct pulses of current, and these are usually referred to as strokes.

The process that culminates in a lightning flash begins with the formation of an ionized column called a leader which travels out from a region where the electric field is so high that it initiates progressive breakdown; this critical field is thought to be about 900kV/m for water droplets or 500kV/m for ice crystals. For a negative discharge to earth the column advances in zigzag steps (hence the name stepped leader) each about 50m long and separated by pauses of 40 - 100ms.

The diameter of the stepped leader is between 1m and 10m although the current, which is low (about 100A), is probably concentrated in a small highly ionized core, about 1cm diameter. The average velocity of propagation is 1.5×10^5m/s. The leader may form branches on its downward path to the ground. When a branch is near to the ground, it causes high fields to form at projections such as trees and buildings and these then send up leaders, one of which will make contact with the tip of the downward propagating leader. This has the effect of closing a switch and the position in the channel where it occurs is known as the switching point. When that occurs, a return stroke is initiated which retraces and discharges the leader channel at a velocity of about 5×10^7m/s. This initial return stroke is characterized by a current pulse of high amplitude accompanied by high luminosity. After the first return stroke, further strokes may occur as higher areas of the negative charge regions are discharged; the dart leaders for these usually traverse the same path as the first but in one continuous sweep at a velocity of 2×10^6 m/s.

Return stroke modeling indicates that there is a decrease of the value of the return stroke current versus an increase in altitude (Reference 7.5.2). This is typical of a negative flash to open ground, but over mountains and tall buildings the leader may be of the upward moving type, originating from a high point such as a mountain peak. When such a leader reaches the charge pocket in the cloud, a return stroke is initiated and subsequent events follow the same pattern as for initiation by a downward moving leader. Thus the "switching" point is near the ground for downward leaders but near the charge pocket in the cloud for upward leaders. This can make a significant difference to the waveform and amplitude of the current experienced by an airborne vehicle that forms part of the lightning path.

7.2.2 The negative flash to ground

An example of the return stroke current in a severe negative flash is sketched in Figure 7-2(a). The number of strokes in a negative flash is usually between 1 and 11, the mean value being 3; the maximum number is up to 24. The total duration is between about 20ms and 1s, with a mean value of 0.2s. The time interval between the strokes is typically about 60ms. There is some correlation among these parameters, the flashes with the most strokes tending also to be the longest duration. The rise time of the first stroke is about 2μs, with a decay time (to half the peak amplitude) of 45μs. Subsequent strokes in the flash tend to have a higher rate-of-rise although lower peak amplitudes than the initial stroke and they can therefore be significant for inducing voltages in wiring, where the inductively coupled voltages are proportional to the rate of change of the lightning current.

Near the end of some of the strokes in a negative flash, there is often a lower level current of a few kA persisting for several milliseconds, known as an "intermediate current," as shown in Figure 7-2(a). After some strokes a "continuing current" of 100-400A flows with a duration of 100-800ms, so that there is substantial charge transfer in this phase. It is particularly common for there to be a continuing current after the last stroke.

It is generally thought that before a restrike can occur the continuing current must cease, as illustrated after stroke 5 in Figure 7-2(a).

7.2.3 The positive flash to ground

Positive flashes to ground generally occur less frequently than negative flashes, however in certain geographic locations there may be more positive flashes to ground. Present standards have assumed an average of around 10% positive flashes to ground. Positive flashes are usually initiated by upward moving leaders and more commonly occur over mountains than over flat terrain. Normally they consist of one stroke only. They have slower rise times than negative flashes, with high peak current and charge transfer; the duration is longer than a single stroke of a negative flash but usually shorter than a complete negative flash. The stroke may be followed by a continuous current.

An example of the current in a positive flash is shown in Figure 7-2(b); it is a moderately severe example although not the "super flash" which occurs occasionally. Typically the rise time of a positive flash is 20μs and the total duration 0.1s. Although positive flashes are far less globally frequent than negative, they have to be taken into consideration in the selection of design and test parameters.
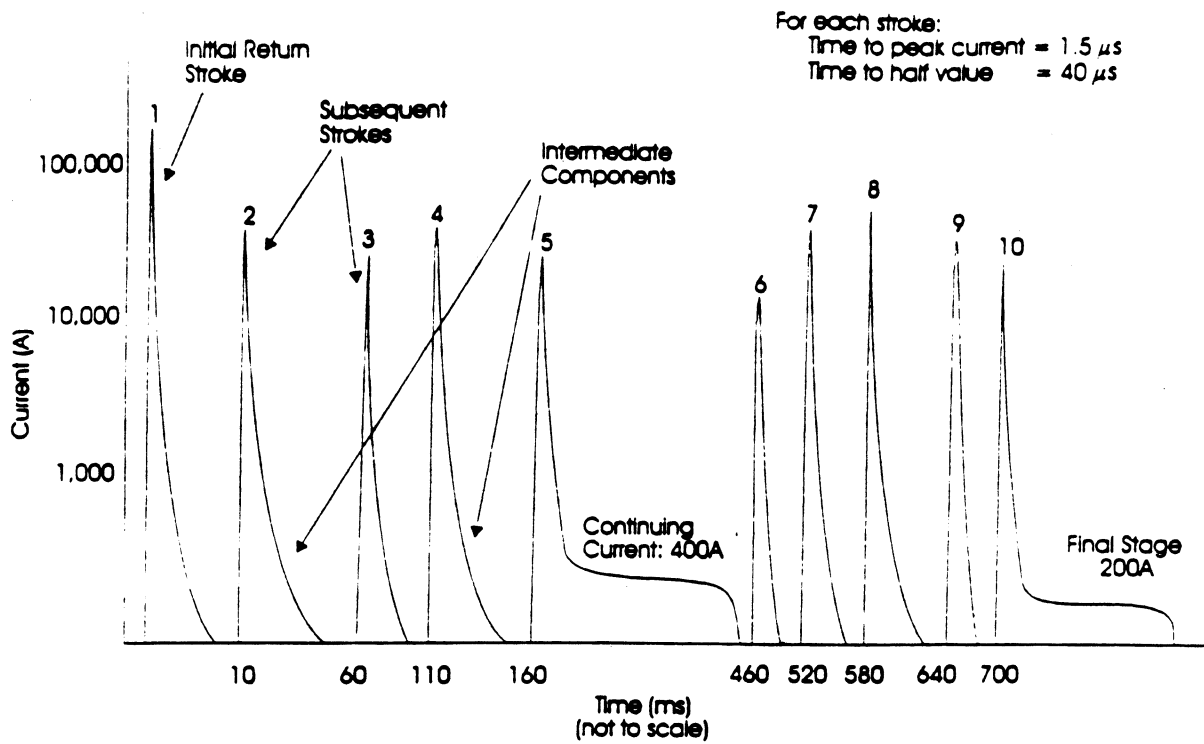
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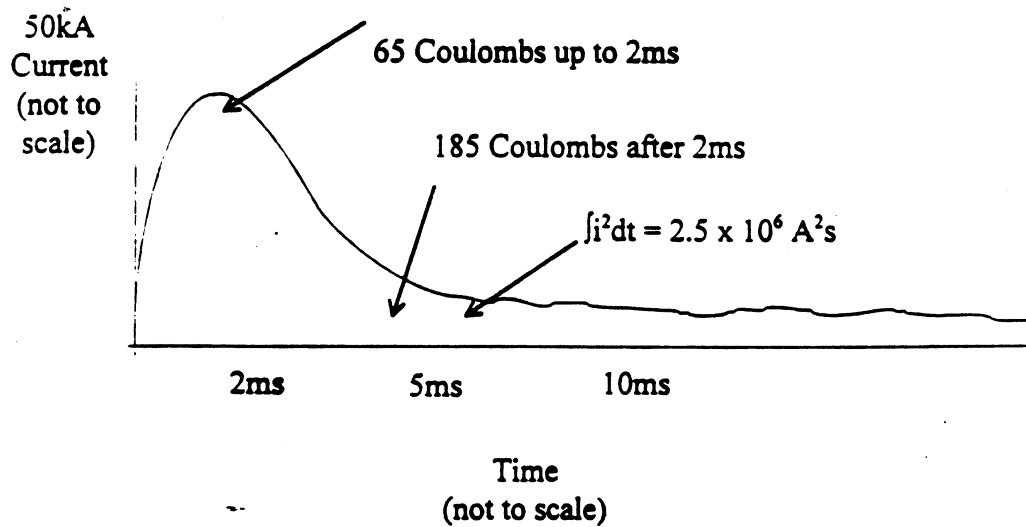Figure 7-2(a).   Model of a severe negative lightning flash current waveforms.

Figure 7-2(b).   Model of a moderate positive lightning flash current waveform.

7.3   Inter and Intra Cloud Flashes

The preceding discussion relates to flashes of either polarity to ground since most available knowledge relates to flashes of that type. Instrumented aircraft have been employed in U.S.A. and France to record the characteristics of cloud flashes. Generally speaking, the conclusion is that cloud flashes are less severe than flashes to the ground, certainly with respect to peak current, charge transfer and action integral. However, the airborne measurements show some evidence that over a portion of some pulse wavefronts the rate-of-rise for a short time (less than 0.4μs) may be higher than the figure related to cloud to ground flashes. Short pulses of low amplitude but high rate-of-rise have been observed during intra-cloud flashes. Similar pulses due to charge redistribution in a cloud have been observed between return stokes in flashes to ground.

For intra-cloud discharges, recoil streamers of up to 60kA peak current have been recorded, but are more typically 20-30kA (Reference 7.5.3). A typical intra-cloud lightning flash is presented in Figure 7-3. The pulses occurring during the initial attachment phase might also occur in negative cloud to ground flashes.
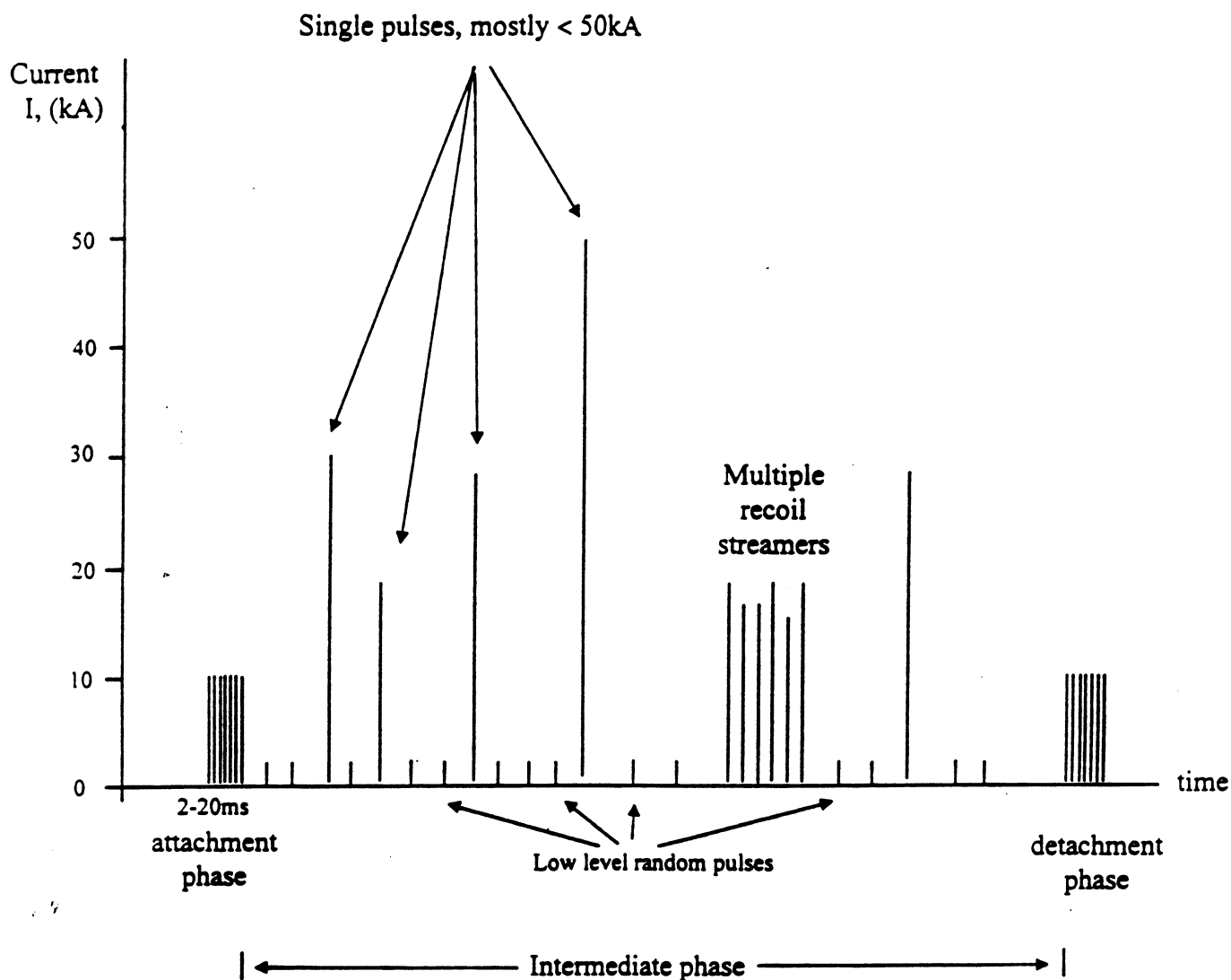
Figure 7-3. Typical intra-cloud lightning flash to an aircraft.

7.4 Flash Parameters

Most of the available statistical data are from cloud to ground and ground to cloud lightning flashes. The relevant data are presented in Tables 7-1 and 7-2 divided into negative and positive flashes. The tables include statistical data for the lightning currents and all related parameters of interest for the definition of the external environment. For a given flash or stroke parameter, the tables show that as the magnitude increases, the percentage of occurrence decreases. The extreme parameters do not occur together in one flash.

Less data are available with respect to inter and intra cloud lightning flashes (Section 7.3). The available data indicate that the cloud to ground and ground to cloud flashes represent the most severe lightning threat to the aircraft with the only exception being the high rate of rise pulse wavefronts measured during the initial and the final attachment phases to the Instrumented aircraft referred to in Section 7.3. Similar pulses with fast rates of change have also been reported in cloud-to-earth flashes which convey negative charge to the earth.

In addition to the lightning currents, electric fields exist before and during a lightning strike event. Initially, these fields result in breakdown of the air to form the attachment and may also cause breakdown of dielectric materials on an aircraft. The magnitudes of these fields are dependent upon air breakdown thresholds and range between 400 and 3000kV/m, with rates of rise of up to 1000kV/m/μs.

7.5 References

7.5.1   "The Distribution of Electricity in Thunderclouds"
Malan, D. J. and Schonland, B. F. J.:
Proc. Roy. Soc. London, A 209 (1951)

7.5.2   "Lightning"
Uman, M. A.
McGraw Hill Book Company, London 1988

7.5.3   "Aircraft Triggered Lightning: Process Following Strike Ignition that Affect Aircraft"
Mazur, V. and Moreau J. P.
Journal of Aircraft, Volume 29, Nr. 4, July/August 1992, pages 575-580.

Table 7-1. Parameters for negative lightning flashes measured at ground.

Parameters	Unit	Lightning Parameters		
Negative Flashes		95%	50%	5%
Number of strokes		1 - 2	3 - 4	12
Time intervals between strokes	ms	8	35	140
Flash duration	s	0.03-0.04	0.2	1
Charge in flash	C	1.3	7.5	40
Negative first stroke				
Peak current	kA	14	30	80
Peak rate-of-rise	A/s	5.5×10^9	1.2×10^{10}	3.2×10^{10}
Time to peak	µs	1.8	5.5	18
Time to half value	µs	30	75	200
Impulse charge	C	1.1	5.2	24
Action integral	A^2s	6×10^3	5.5×10^4	5.5×10^5
Negative subsequent strokes				
Peak Current	kA	4.6	12	30
Peak rate-of-rise	A/s	1.2×10^{10}	4×10^{10}	1.2×10^{11}
Time to peak	µs	0.22	1.1	4.5
Time to half value	µs	6.5	32	140
Impulse charge	C	0.2	1.4	11
Action integral	A^2s	5.5×10^2	6×10^3	5.2×10^4
Continuing current		**98%**	**50%**	**2%**
Amplitude	A	33	140	520
Duration	s	0.058	0.16	0.40
Charge	C	7	26	110

Note 1: The above lightning parameters do not necessarily occur together in one flash.
Note 2: The percentage figures represent percentiles, that is, the percentage of events having a greater amplitude than those given.

Table 7-2. Parameters for positive lightning flashes measured at ground.

Parameters	Unit	Lightning Parameters		
Positive Flashes		95%	50%	5%
Flash duration	ms	14	85	500
Total charge	C	20	80	350
Positive Stroke		95%	50%	5%
Peak current	kA	4.6	35	250
Peak rate-of-rise	A/s	2×10^8	2.4×10^9	3.2×10^{10}
Time to peak	μs	3.5	22	200
Time to half value	μs	25	230	2000
Impulse charge	C	2	16	150
Action integral	$A^2 s$	2.5×10^4	6.5×10^5	1.5×10^7

Note: The individual parameters listed above do not necessarily occur together in one flash.

8.0 LIGHTNING INTERACTIONS WITH AIRCRAFT

A lightning strike to an aircraft will either be triggered (i.e. initiated) by the presence of the aircraft in a strong electric field and will originate at the aircraft, or will occur as a result of encounter with a naturally occurring leader which originated elsewhere.

8.1 Strike Occurrence

The probability of a lightning strike to an aircraft depends on various parameters, e.g. the local climate, flight profile, type of aircraft. From a significant sample of reported strikes to large transport aircraft operating in scheduled airline service, the average probability of a lightning strike has been estimated to be approximately one strike in every 10,000 flight hours. A separate study of transport aircraft experience within a region known to be prone to lightning estimated the average probability of a lightning strike to be approximately one strike in every 1,000 flight hours. Therefore, the average probability of a lightning strike to a given aircraft will be likely to fall somewhere between one strike per 1,000 and 20,000 flight hours.

These data are based on reported strikes, which get noticed because of bright light, (especially at night), loud noises or associated physical damage effects or interference or damage to cockpit avionics. Other strikes to aircraft undoubtedly occur but go unnoticed or are not reported.

8.2 Aircraft Intercepted Lightning

An intercepted flash can occur when a lightning leader advances sufficiently close to the aircraft to be diverted to it. This latter interaction can occur for all types of discharges: inter, intra and cloud to ground.

As noted, most intra-cloud flashes are probably less severe than cloud-to-ground flashes. If we consider only ground flashes however, it is likely that the parameters at the altitude of an aircraft in flight will be different from those measured at stations on the ground. This is because the lightning channel acts as a lossy transmission line and the return stroke current experiences changes in both shape and amplitude as it develops from the switching point towards the vehicle.

8.3 Aircraft Triggered Lightning

Aircraft may also trigger the flashes that they interact with in regions where there are strong electric fields. These flashes would not have occurred in the absence of the aircraft. Many storm cloud penetrations made during in-flight measurement programs (References 8.7.1, 8.7.2, and 8.7.3) produced lightning strikes which were probably triggered by the aircraft.

It is thought that most triggered lightning flashes have a lower amplitude than most cloud to ground flashes. The latter will, however, continue to be the basis of protection design.

8.4 Swept Channel Process

If a fast moving vehicle such as an aircraft experiences a direct strike, then throughout the flash, the point(s) of arc attachment is likely to be swept backwards along the vehicle, since the lightning channel tends to remain stationary relative to the surrounding air. Except possibly on smooth unpainted surfaces, this movement of the attachment point is not continuous but progresses in a series of discrete irregular steps. The dwell time at any particular step is not likely to exceed 50ms, being chiefly dependent on the nature of the surface and the velocity of the vehicle. The movement of the points of arc attachment is known as the "Swept Channel" phenomenon. This area of the aircraft is defined as the Swept Stroke Zone. For an airspeed of 300 knots an aircraft moves through its own length of (say) 15m in 100ms, which is well within the average duration of a lightning flash. When the lightning channel has swept back to a trailing edge, it can progress no further and may remain there, or "hang on," for the remainder of the flash. When the entry and exit portions of the lightning channel have swept aft to trailing edges, the channel may rejoin behind the aircraft and the aircraft is no longer in the lightning current path.

The sweeping action of the channel can have several consequences. For example, inboard areas of an aircraft wing such as those behind an inboard engine will be subjected to the Swept Channel phenomenon because they are in the path of a sweeping channel. On the other hand, the effects of the flash are spread out over a considerable number of points so that except for an attachment point at a trailing edge, no single point receives the full energy of the flash. The proportion of the flash experienced by any particular point depends on its location on the vehicle surface and this has lead to the concept of dividing the surface into lightning strike zones depending on the probability of initial attachment, sweeping and hang-on.

8.5 Nearby Lightning

Nearby flashes might cause some indirect effects. These effects, due predominantly to magnetic field coupling, are in general significantly smaller than those caused by direct lightning strikes to the aircraft.

The magnetic fields (H-fields), which can be expected from a nearby lightning strike, can be estimated by the following expression:

$$H = \frac{I}{2\pi r}$$

where:

H = field strength in amperes per meter

I = lightning current in amperes

r = distance between the lightning channel and the aircraft in meters.

8.6 Lightning Strike Zones

Due to the lightning attachment process, not all locations on an aircraft are exposed to the same lightning environment components. To optimize lightning protection, the

aircraft will, therefore, be divided into different lightning strike zones. These zones will then be protected against their applicable components of the lightning environment.

In general an aircraft can be divided into the following zones:

Zone 1A:	First Return Stroke Zone,
Zone 1B:	First Return Stroke Zone with Long Hang-On,
Zone 1C:	Transition Zone for First Return Stroke,
Zone 2A:	Swept Stroke Zone,
Zone 2B:	Swept Stroke Zone with Long Hang-On, and,
Zone 3:	Current Conduction Zone.

Zone definitions and methods of locating them on particular aircraft are given in Reference 4.1.

8.7   References

8.7.1   "New Results for Quantification of Lightning/Aircraft Electrodynamics"
F. L. Pitts, R. A. Perala, L. Dee
Electromagnetics Vol.7, 1987.

8.7.2   "Analysis of Correlated Electromagnetic Fields and Current Pulses during Airborne Lightning Attachments"
J. S. Reaser, A. V. Serrano, L. C. Walko, and H. D. Burket
Electromagnetics, Vol. 7, 1987.

8.7.3   "Analysis of the First Milliseconds of Aircraft Lightning Attachments"
J. P. Moreau, J. C. Alliot
11th International Aerospace and Ground Conference on Lightning and Static Electricity, Dayton, OH, 1986.

9.0 IDEALIZED STANDARD LIGHTNING ENVIRONMENT

9.1 General

The environment waveforms presented in this chapter represent idealized environments which are to be applied to the aircraft for purposes of analysis and testing. The waveforms are not intended to replicate a specific lightning event, but they are intended to be composite waveforms whose effects upon aircraft are those expected from natural lightning.

The standard lightning environment is comprised of individual voltage waveforms and current waveform components which represent the important characteristics of the natural lightning flashes.

In the waveform descriptions that follow, parameters of particular importance to the effects (direct or indirect) to be considered, are included whereas other parameters are omitted. For example, for direct effects evaluations, peak current amplitude, action integral and time duration are of primary importance, whereas for indirect effects evaluations, rates of current rise and decay as well as peak amplitude are important.

Not all surfaces of an aircraft need to be designed to survive the same lightning threat. The applicable design parameters and test waveforms for each zone are presented in Section 9.4.

This section presents waveforms and their related parameters to be applied for aircraft structures and equipment lightning protection design and verification purposes.

9.2 Idealized Voltage Waveforms

The idealized Voltage Waveform represents that portion of the electric field important for assessment of lightning attachment to aircraft structures.

The basic Voltage Waveform to which vehicles are subjected for analysis or test is one that represents an electric field which increases until breakdown occurs either by puncture of solid insulation such as the fiberglass skin of a radome, or flashover through the air or across an insulating surface. The path that the flashover takes, either puncture or surface flashover, depends in part on the waveshape of the electric fields.

It is sometimes necessary to determine the critical voltage amplitude at which breakdown occurs. This critical voltage level depends upon both the rate-of-rise of voltage and the rate of voltage decay. Two examples are: (1) determining the strength of the insulation used on electrical wiring; and, (2) determining the points from which electrical streamers appear on a vehicle as a lightning flash approaches.

Since there is a wide range of possible electric field waveforms produced by natural lightning, two voltage waveforms have been established, representing fast and slow rates of field rise. These are Waveform A described in Section 9.2.1 and Waveform D presented in Section 9.2.4.

Two other high voltage Waveforms designated B and C are described in Sections 9.2.2 and 9.2.3 respectively. The first is a full voltage Waveform to be used wherever an impulsive field that does not reach breakdown is required, i.e. streamer testing. The second Waveform is employed for fast front model tests. Waveform D can also be used for slow front model tests.

It has been determined in laboratory testing that the results of attachment point testing of aircraft models are influenced by the voltage Waveform. Fast rising waveforms (rise in the order of a few microseconds) produce a relatively small number of attachment points, usually to the apparent high field regions on the model and may produce a greater likelihood of puncture of dielectric skins. Slow front waveforms (in the order of hundreds of microseconds) produce a greater spread of attachment points, possibly including attachments to lower field regions.

The voltage waveforms presented in this Adversary Circular are intended for evaluation of possible lightning attachment locations and/or dielectric breakdown paths through non-conducting surfaces or structures.

9.2.1 Voltage Waveform A

This waveform rises at a rate of 1000 kV/μs ($\pm$ 50%) until its increase is interrupted by puncture of, or flashover across, the object under test. At that time the voltage collapses to zero. The rate of voltage collapse or the decay time of the voltage if breakdown does not occur (open circuit voltage of a lightning voltage generator) is not specified. The voltage Waveform A is shown in Figure 9-1.

9.2.2 Voltage Waveform B

Waveform B is a 1.2 x 50μs waveform which is the electrical industry standard for impulse dielectric tests. It rises to crest in 1.2μs (± 20%) and decays to half of crest amplitude in 50μs (± 20%). Time to crest and decay time refer to the open circuit voltage of a lightning voltage generator, and assume that the waveform is not limited by puncture or flashover of the object under test. This waveform is shown in Figure 9-2.

9.2.3 Voltage Waveform C

This is a chopped voltage waveform in which breakdown of the gap between an object under test and the test electrodes occurs at 2μs (± 50%). The amplitude of the voltage at time of breakdown and the rate-of-rise of voltage prior to breakdown are not specified. The waveform is shown in Figure 9-3.

9.2.4 Voltage Waveform D

The slow fronted waveform has a rise time between 50 and 250μs so as to allow time for streamers from an object to develop. It should give a higher strike rate to the low probability regions than otherwise might have been expected. This waveform is shown in Figure 9-4.
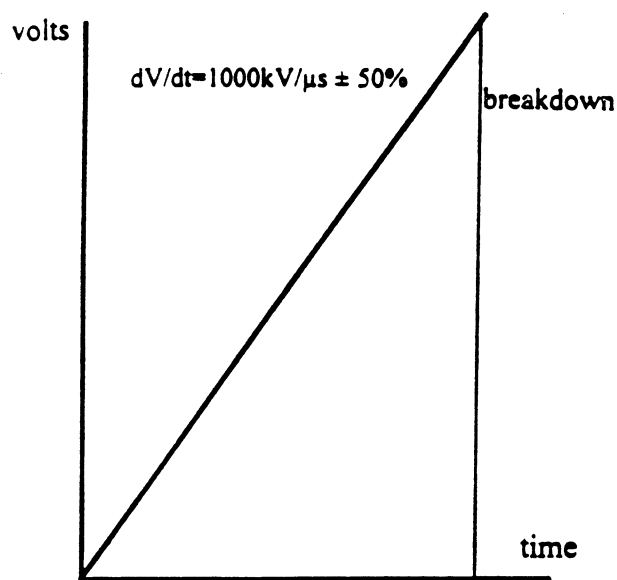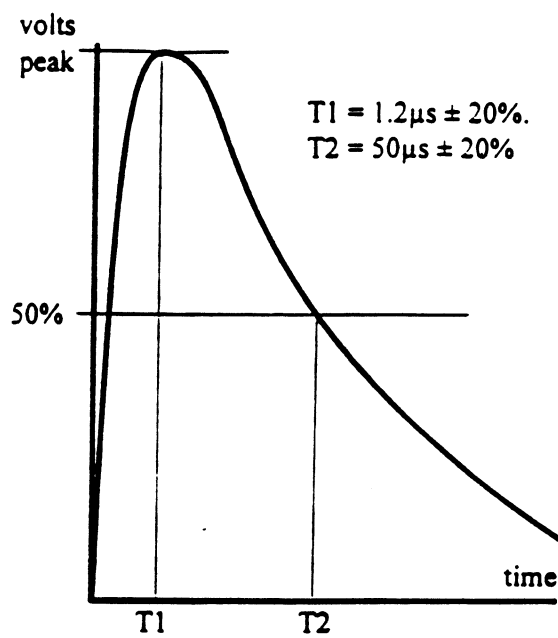
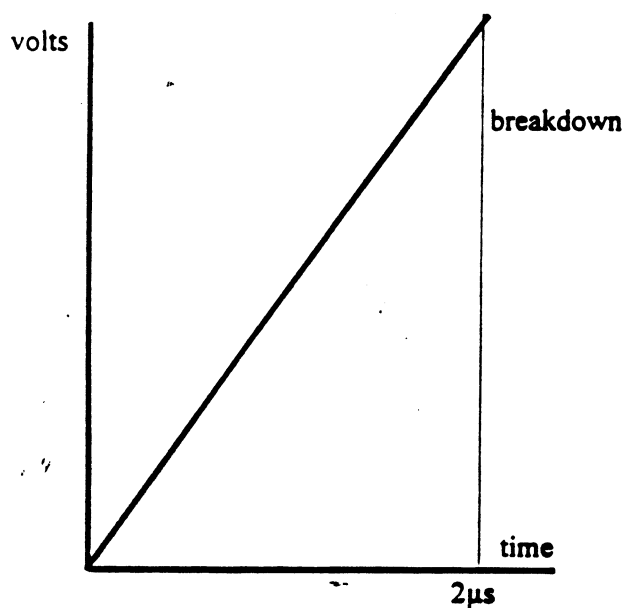Figure 9-1. Voltage Waveform A.

Figure 9-2. Voltage Waveform B.

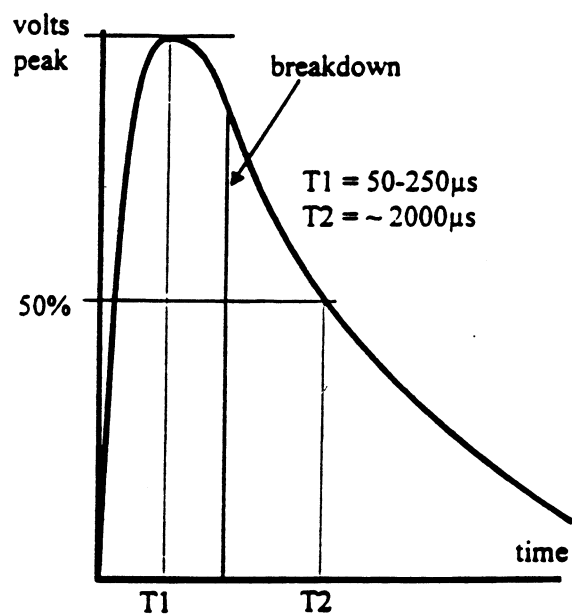Figure 9-3. Voltage Waveform C.

Figure 9-4. Voltage Waveform D.

9.3 External Idealized Current Components

The external lightning environment is comprised of current components A, A_h, B, C, D and H, and the Multiple Stroke (MS) and Multiple Burst (MB) Waveform sets. The MS is comprised of components D and D/2, and the MB is comprised of component H pulse sequences.

Current components A, B, C, and D comprise the lightning flash current waveform for evaluating direct effects and are shown in Figure 9-5. Current components A and D, and Waveform sets MS and MB are applicable for evaluating indirect effects. The latter two are shown in Figures 9-14 and 9-15.

The current components are defined as follows:

9.3.1 Current component A - first return stroke

This waveform combines the severe parameters of both the negative and the positive first return strokes. It occurs most frequently to aircraft flying at lower altitudes.

For analysis purposes and indirect effect considerations the double exponential waveform shown in Figure 9-6(a) shall be applied.

This waveform is defined mathematically by the double exponential expression shown below:

$$i(t) = I_0\left(e^{-\alpha t} - e^{-\beta t}\right)$$

where:

$I_0 = 218,810$ A
$\alpha = 11,354$ s^{-1}
$\beta = 647,265$ s^{-1}
t is time (s)

The frequency content of current component A is given in Figure 9-6(b).

For direct effects testing purposes component A can be simulated by an oscillatory or unidirectional waveform like those presented in the Figures 9-7(a) and 9-7(b). The current must have an amplitude of 200kA (± 10%) with a rise time of up to 50µs (the time between 10% and 90% of peak amplitude). The action integral has to be 2 x 10^{6}A^{2}s (± 20%), and the total time to 1% of peak value shall not exceed 500µs.

The action integral, $\int i^2 dt$, is a critical factor in the extent of damage. It relates to the energy deposited or absorbed in a system. However, the actual energy deposited cannot be defined without a knowledge of the resistance of the system. For example, the instantaneous power dissipated in a resistor is $i^2 R$, and is expressed in Watts. For the total energy expended, the power must be integrated over time to get the total Watt-seconds (or Joules). Action integral can be applied to any resistance value to identify the total energy deposited.

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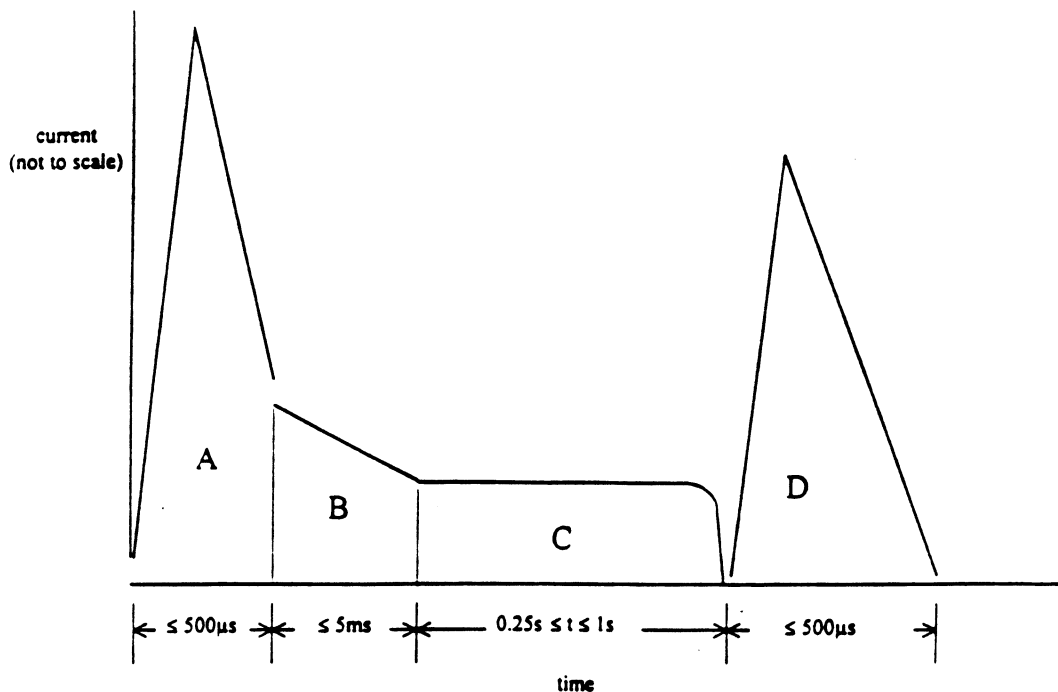
COMPONENT A (First Return Stroke)

Peak Amplitude	:	200kA (± 10%)
Action Integral	:	$2 \times 10^6 A^2 s$ (± 20%) (in 500μs)
Time Duration	:	≤ 500μs

COMPONENT B (Intermediate Current)

Max. Charge Transfer	:	10 Coulombs (± 10%)
Average Amplitude	:	2kA (± 20%)
Time Duration	:	≤ 5ms

COMPONENT C (Continuing Current)

Amplitude	:	200 - 800A
Charge Transfer	:	200 Coulombs (± 20%)
Time Duration	:	0.25 to 1 s

COMPONENT D (Subsequent Return Stroke)

Peak Amplitude	:	100kA (± 10%)
Action Integral	:	$0.25 \times 10^6 A^2 s$ (± 20%) (in 500μs)
Time Duration	:	≤ 500μs

Figure 9-5. Current components A through D for Direct Effects testing.
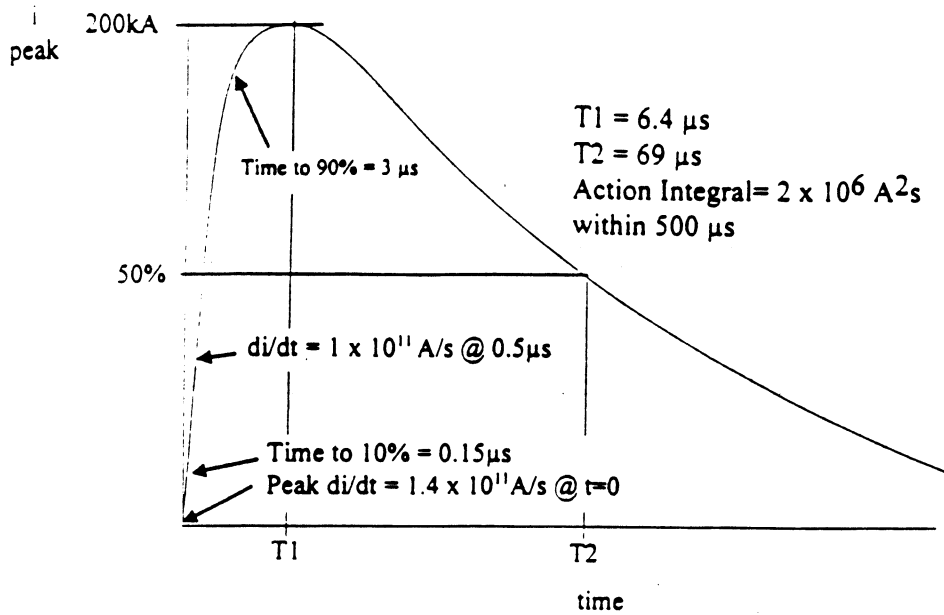
Figure 9-6(a). Current component A for analysis and indirect effects test purposes.
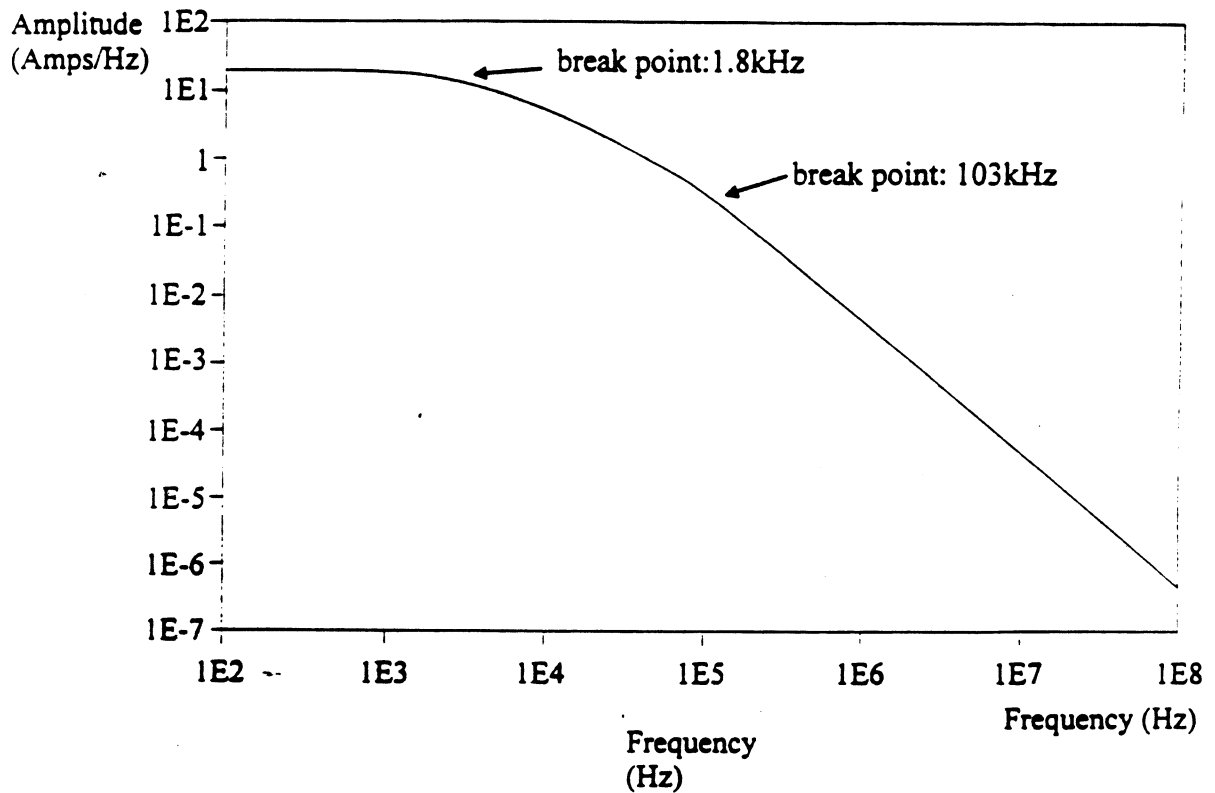
In the figure:

$T1 = 6.4\ \mu s$

$T2 = 69\ \mu s$

Action Integral= 2×10^6 A^{2}s within 500 μs

Time to 90% = 3 μs

$di/dt = 1 \times 10^{11}$ A/s @ 0.5μs

Time to 10% = 0.15μs

Peak $di/dt = 1.4 \times 10^{11}$ A/s @ t=0

break point:1.8kHz

break point: 103kHz

Figure 9-6(b) Frequency content (amplitude spectrum) of component A.

I peak
200kA

Action integral 2.0×10^6 A^2s
within 500μs

time
≤ 500μs
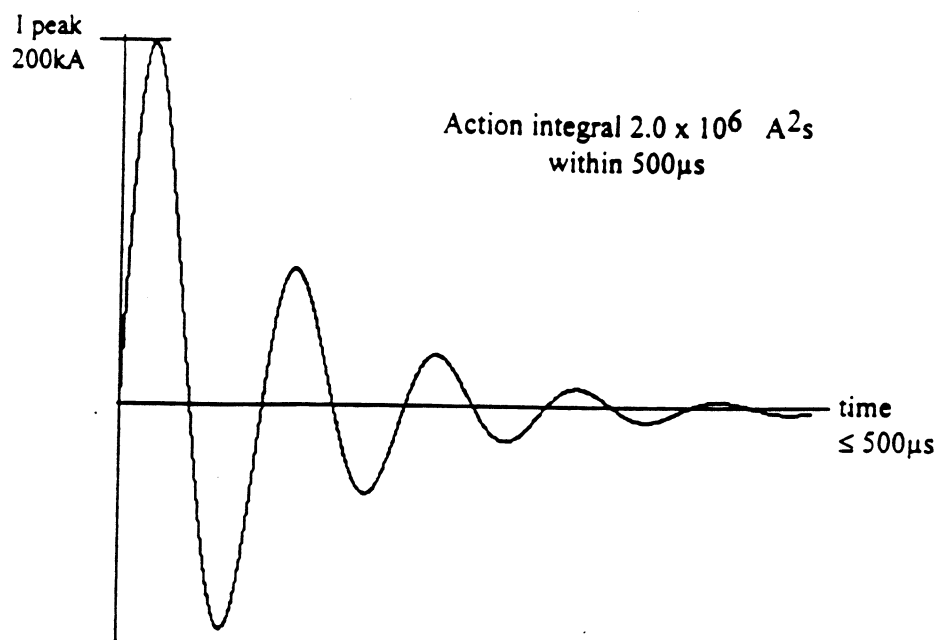
Figure 9-7(a). Damped sinusoidal current.

200kA

180kA

Action integral 2.0×10^6 A^2s
within 500μs

i_p
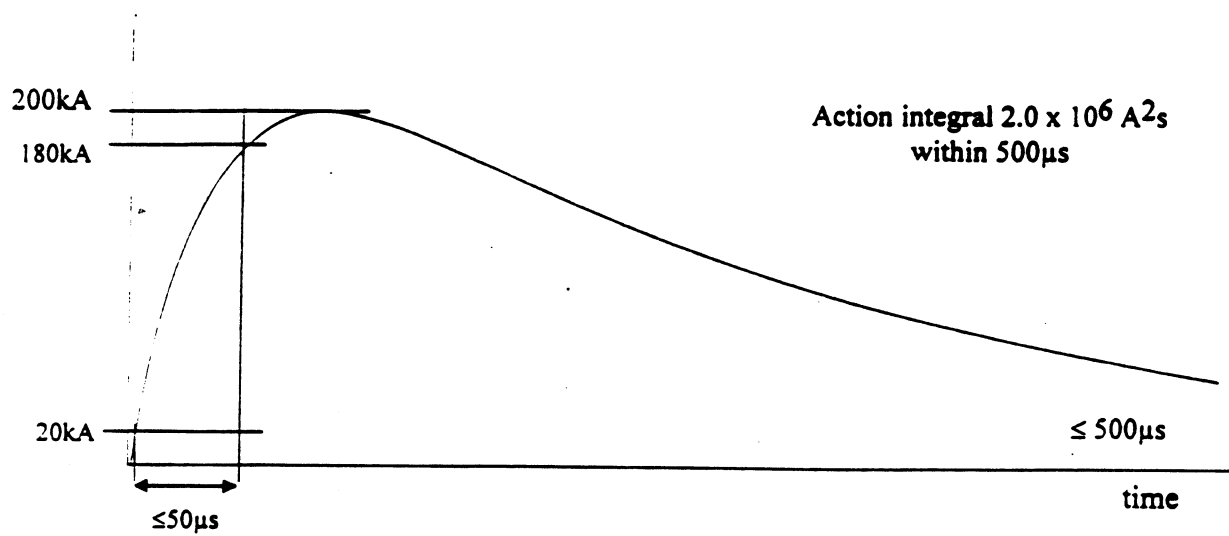
20kA

≤ 500μs

time

≤50μs

Figure 9-7(b). Unipolar current.

9.3.2 Current component A_h - transition zone first return stroke

The amplitude and waveform of the first return strokes, which might hit an aircraft, depend on the flight altitude. In general, lower amplitudes and action integrals can be expected at higher altitudes.

For analysis purposes a double exponential as shown in Figure 9-8(a) shall be applied. This waveform is applicable in the transition Zone 1C and represents the estimated shape of the first return stroke (Component A) at higher altitudes.

This waveform is defined mathematically by the following double exponential function:

$$i(t) = I_0\left(e^{-\alpha t} - e^{-\beta t}\right)$$

where:

$I_0 = 164,903$ A
$\alpha = 16,065$ s^{-1}
$\beta = 858,888$ s^{-1}
t is time (s)

For direct effects testing, component A_h can be simulated by an oscillatory or unidirectional waveform as shown in Figures 9-8(b) and 9-8(c). The current must have an amplitude of 150kA ($\pm$ 10%) with a rise time of up to 37.5μs (the time between 10% and 90% peak amplitude). The action integral has to be 0.8 x 10^{6}A^{2}s ($\pm$ 20%), and the total time for the current to decay to 1% of peak value shall not exceed 500μs.
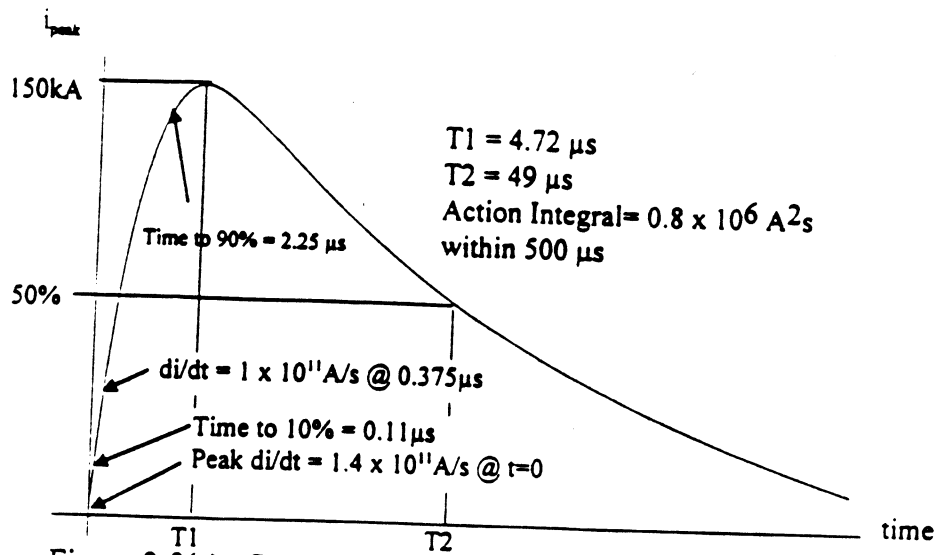
T1 = 4.72 µs
T2 = 49 µs
Action Integral= 0.8 x 10^6 A^2s
within 500 µs

Time to 90% = 2.25 µs

di/dt = 1 x 10^11 A/s @ 0.375µs

Time to 10% = 0.11µs
Peak di/dt = 1.4 x 10^11 A/s @ t=0

Figure 9-8(a). Current component A_h for analysis purposes.

Action integral 0.8 x 10^6 A^2s
within 500µs
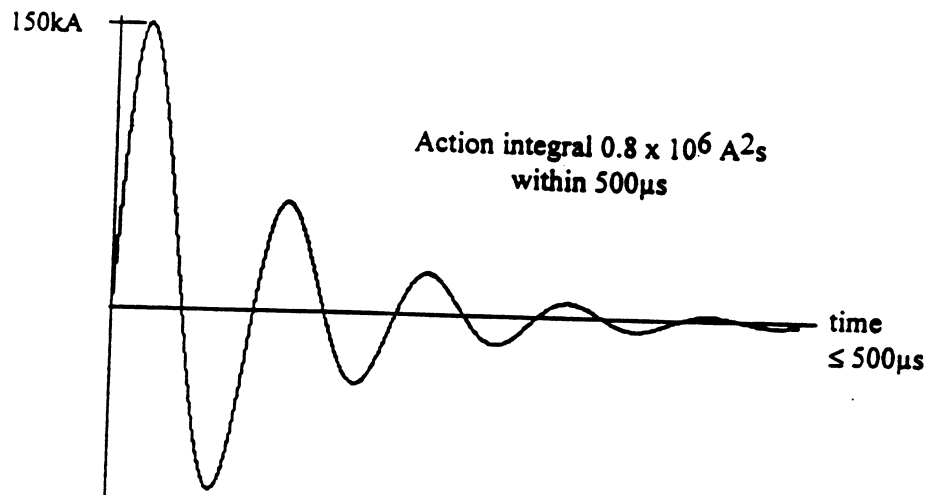
Figure 9-8(b). Example of current component A_h for direct effects, damped sinusoidal
current.

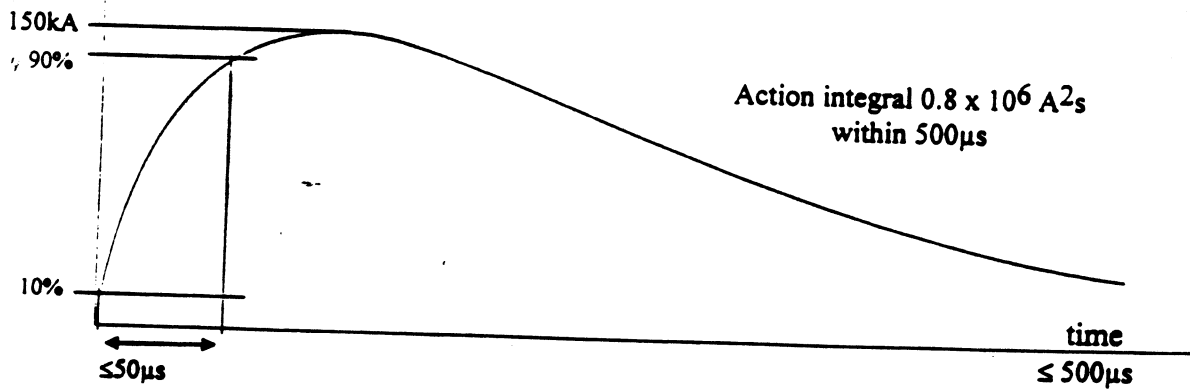Action integral 0.8 x 10^6 A^2s
within 500µs

Figure 9-8(c). Example for current component A_h for direct effects, unipolar current.

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9.3.3 Current component B- intermediate current

This component represents mainly the intermediate currents following some of the negative initial return strokes and/or restrikes (see Figure 7-2).

For analysis purposes a double exponential current waveform could be used as presented in Figure 9-9(a). This waveform is described mathematically by the following expression:

$$i(t) = I_0\left(e^{-\alpha t} - e^{-\beta t}\right)$$

where:

$I_0 = 11,300$ A
$\alpha = 700$ s^{-1}
$\beta = 2,000$ s^{-1}
t is time (s)

For direct effects testing, this component should be unidirectional, e.g. rectangular, exponential, or linearly decaying as shown in Figures. 9-9(b) and 9-9(c). The average amplitude must be 2kA (± 20%) flowing for a duration of 5 milliseconds (± 10%) with a charge transfer of 10 coulombs (± 10%).

9.3.4 Current component C - continuing current

This current component represents the lightning environment that might be caused by the long duration currents which may follow some restrikes of the negative cloud to ground lightning strikes and also the return stroke of the positive cloud to ground lightning flashes.

For analysis purposes, a square waveform of 400A for a period of 0.5s should be utilized (Figure 9-10(a)).

For direct effects testing, the Component C should have a current amplitude between 200 and 800A, a time duration between 0.25 and 1.0s and transfer charge of 200 coulombs (± 20%). This waveform should be unidirectional; e.g. rectangular, exponential or linearly decaying. Some examples are presented in the Figures 9-10(b) and 9-10(c).

9.3.5 Component C* - modified component C

This component represents the portion of component C which flows into an attachment point in Zone 1A or 2A if the dwell time at that point exceeds 5ms. Component C* is primarily used for evaluating melt through of metal skins. Component C* is a current averaging not less than 400A for a period equal to the dwell time minus the 5ms duration of the component B. An example of component C* for test applications is shown in Fig 9-11.

The combination of components A or D, B and C*, therefore represent the dwell time, which may range from 1 to 50ms. For aircraft surfaces finished with conventional primers and paints dwell times of 20ms will normally be sufficient. Other surfaces may experience shorter or longer dwell times. For example, dwell times of 1 to 5ms are typical of lightning attachments to unpainted metal surfaces

when only components A or D, and B would be applied. Dwell times on surfaces covered with especially thick or high dielectric strength coatings may range from 20 to 50 ms.
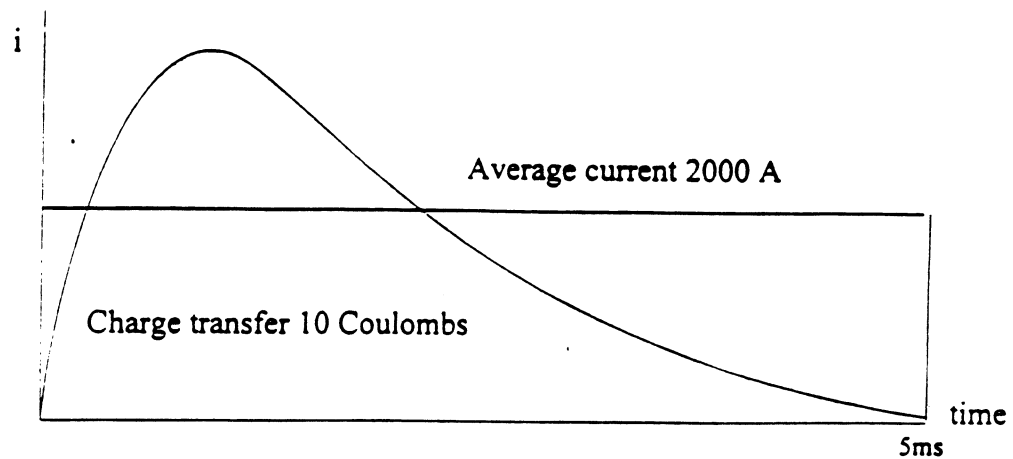

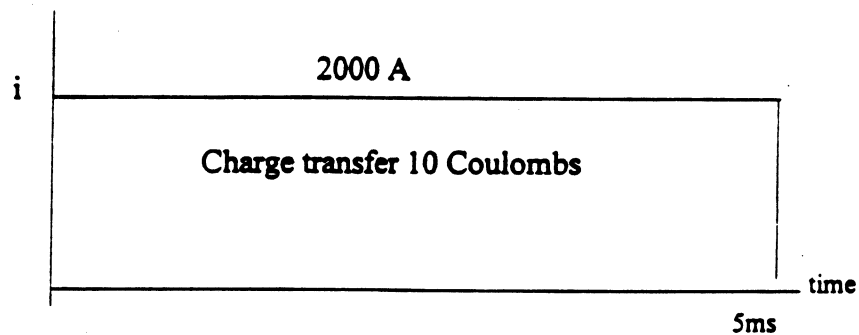Figure 9-9(a). Current component B for testing and analysis purposes.

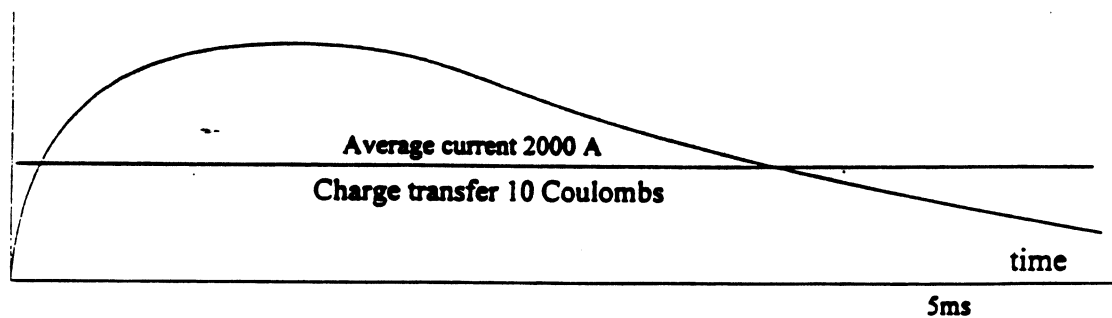Figure 9-9(b). Example of current component B for direct effects testing.

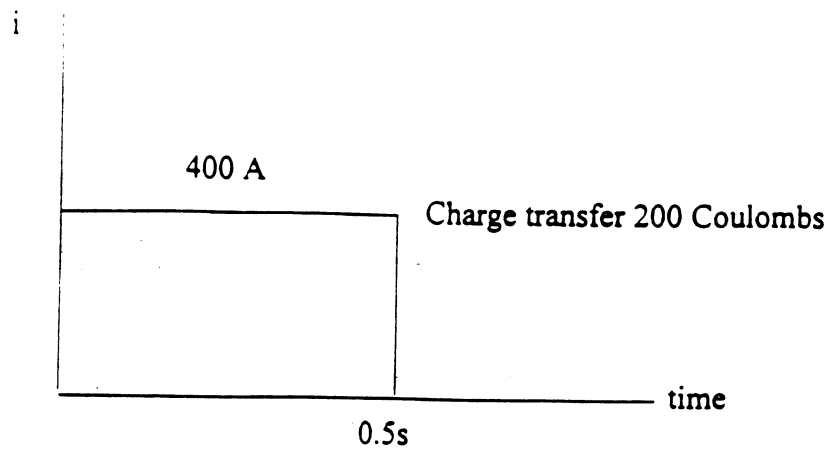Figure 9-9(c). Example of current component B for direct effects testing.

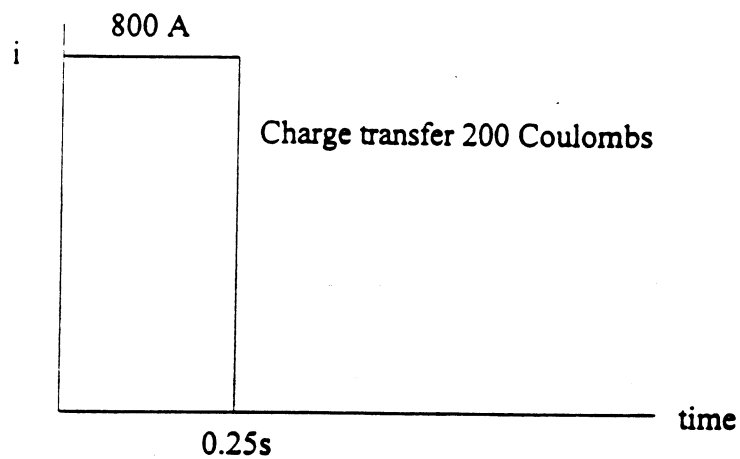Figure 9-10(a). Current component C for analysis purpose.

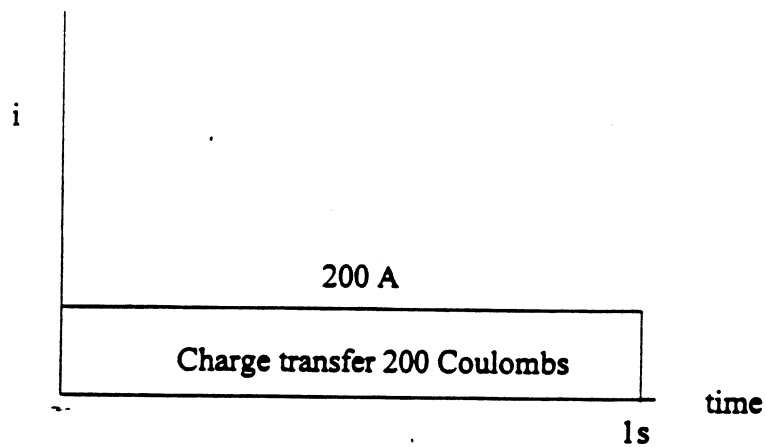Figure 9-10(b). Example of current component C for direct effects testing.

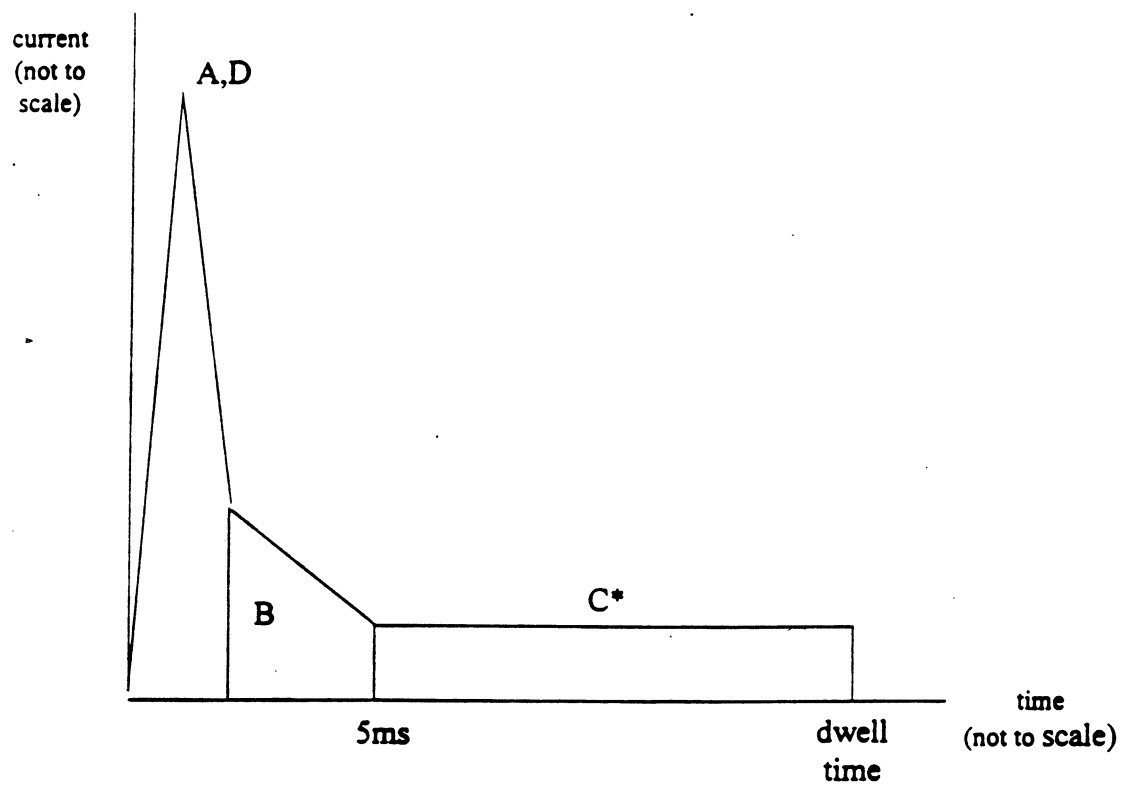Figure 9-10(c). Example of current component C for direct effects testing.

Figure 9-11. Application of current component C*.

9.3.6 Current component D - subsequent stroke current

Current Component D has two applications.

For direct effects assessments current component D represents a subsequent stroke. (Figure 9-5).

For direct effects testing, component D can be simulated by either oscillatory or unidirectional waveforms (Figures 9-13(a) and 9-13(b)) with a total time duration to 1% peak value of 500μs. The amplitude shall be 100kA (± 10%), the rise time shall not exceed 25μs (time between 10% and 90% of the amplitude). The action integral is 0.25 x 10^6A^{2}s (± 20%).

For indirect effects investigations and analysis purposes, the double exponential current waveform presented in Figure 9-12(a) should be used. This waveform represents the initial stroke in the Multiple Stroke waveform set (Fig. 9-14).

The waveform is defined mathematically by the double exponential expression shown below:

$$i(t) = I_0\left(e^{-\alpha t} - e^{-\beta t}\right)$$

where:

$I_0 = 109,405$ A
$\alpha = 22,708$ s^{-1}
$\beta = 1,294,530$ s^{-1}
t is time (s).

The frequency content of component D is given on Figure 9-12(b).
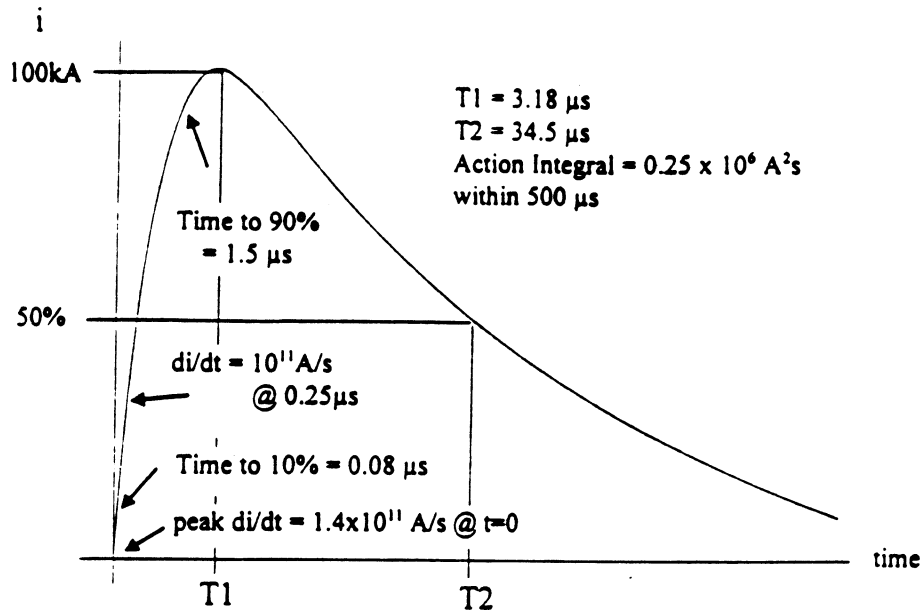
Figure 9-12(a).   Current component D for analysis purpose and indirect effects test purposes.

In the figure:

$$T1 = 3.18\ \mu s$$
$$T2 = 34.5\ \mu s$$
$$\text{Action Integral} = 0.25 \times 10^6\ A^2s$$
$$\text{within 500}\ \mu s$$

100kA

Time to 90% = 1.5 μs

50%

$di/dt = 10^{11}A/s$ @ 0.25μs

Time to 10% = 0.08 μs

peak di/dt = 1.4×10^{11} A/s @ t=0

T1   T2   time
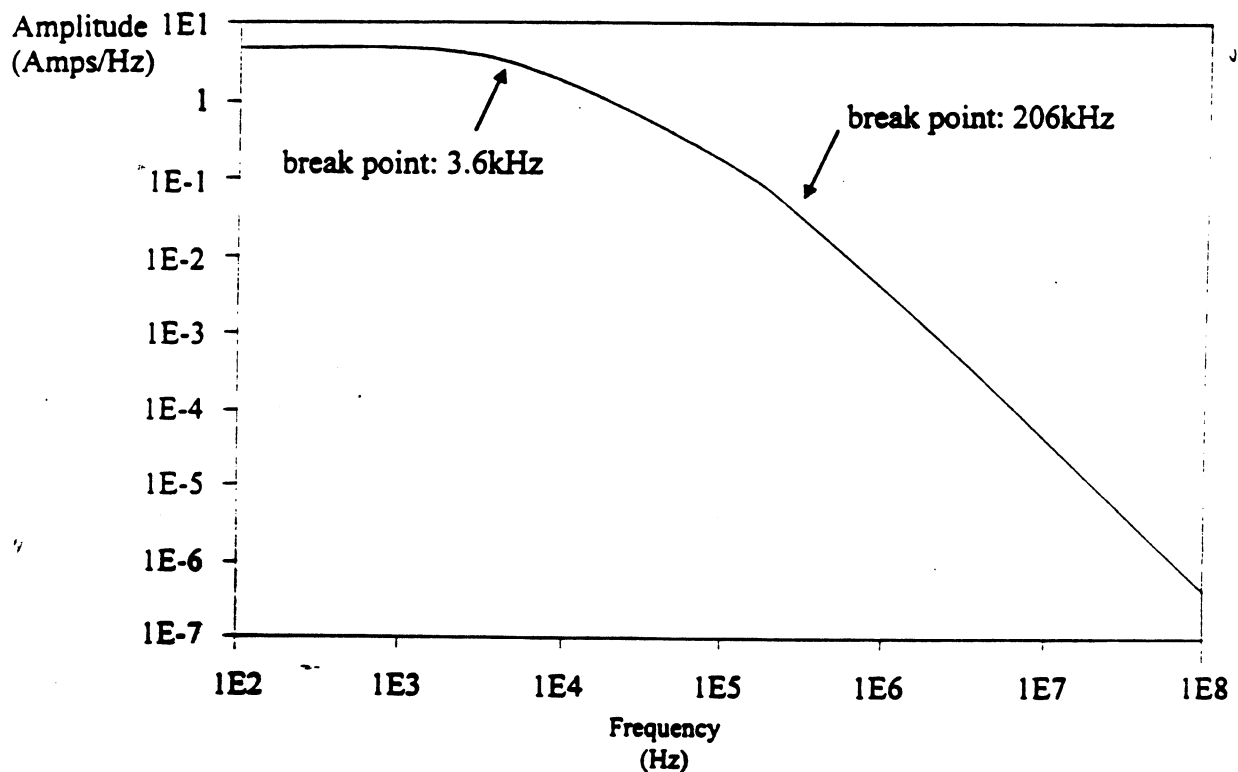
Figure 9-12(b). Frequency content (amplitude spectrum) of component D.

break point: 3.6kHz

break point: 206kHz

Figure 9-13(a).   Damped sinusoidal current.

Figure 9-13(b).   Unipolar pulse.

9.3.7 Multiple Stroke Waveform set

In many cases up to 14 randomly spaced strokes have been observed in negative cloud to ground flashes. Also several pulses of approximately 30kA can occur in a random sequence in an intra-cloud event as illustrated in Figure 7-3.

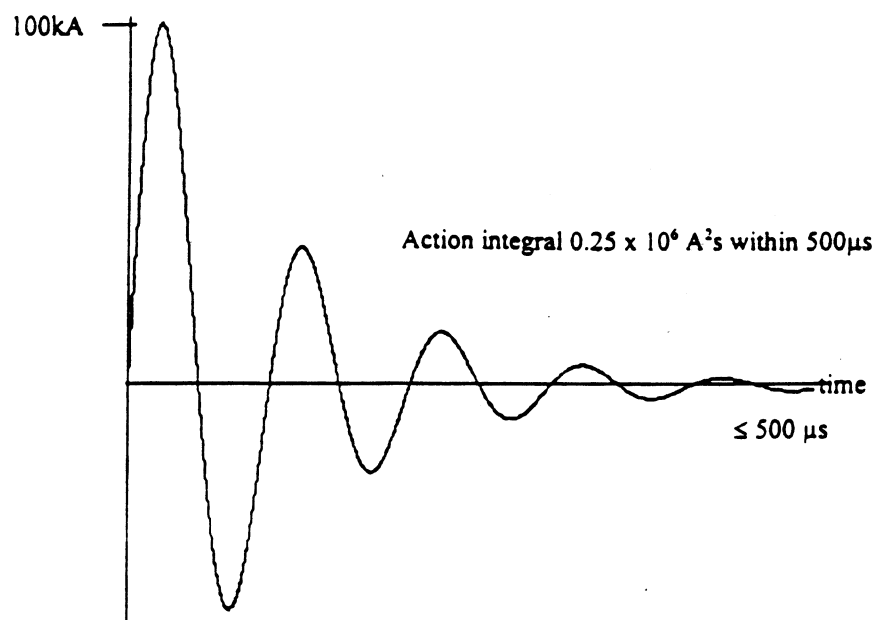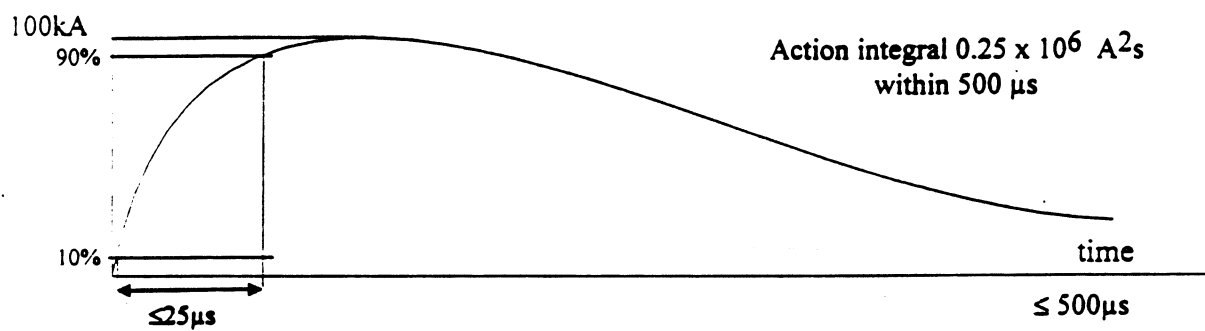The synthesized Multiple Stroke Waveform set is defined as a current component D followed by 13 components D/2 as shown in Figure 9-14. The components D/2 are distributed randomly over a period of up to 1.5 seconds according to the following constraints:

- the minimum time between components is 10 ms,

- the maximum time between components is 200 ms

The D/2 Waveform parameters are identical to the current component D parameters with the exception that $I_0 = 54,703$ A.

The primary purpose of the Multiple Stroke Waveform set is to evaluate system functional upset of systems that may be susceptible to effects of multiple induced transients. It is not necessary that this Waveform set be applied at the defined levels in a test. Instead, the internal environment due to a single component may be determined by analysis or test and the Multiple Stroke combination of induced transients applied to the system/equipment.

The Multiple Stroke Waveform set is used only for indirect effects evaluation.

100 kA

50 kA

10 ms ≤ Δt ≤ 200 ms

D

D/2   D/2   D/2   D/2

1   2   3   13   14
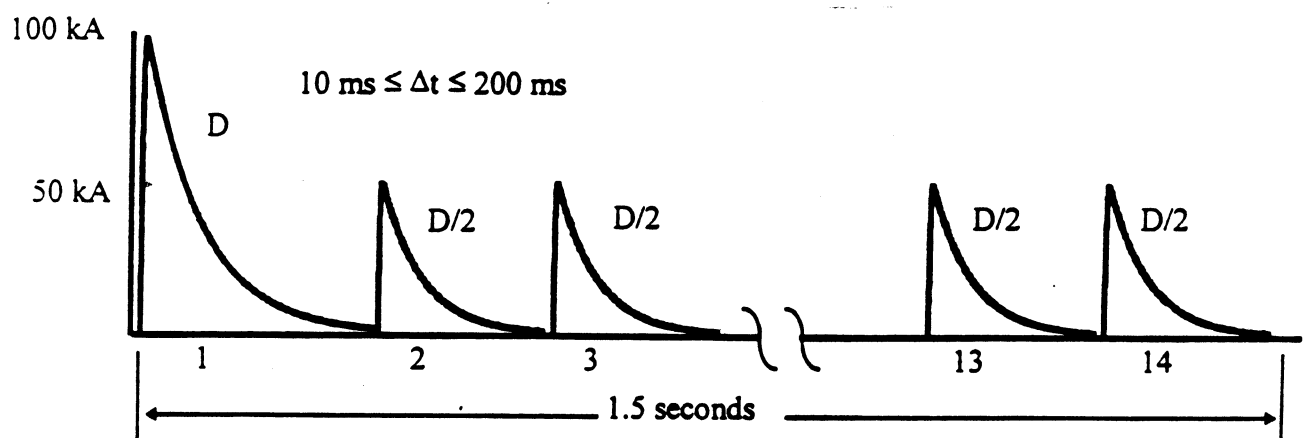
1.5 seconds

One current component D followed by thirteen current component D/2s distributed over a period of up to 1.5 seconds.

Figure 9-14. Multiple Stroke Waveform set.

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9.3.8   Multiple Burst Waveform set

The Multiple Burst Waveform set is comprised of component H waveforms. Component H represents a high rate-of-rise current pulse whose amplitude and time duration are much less than those of a return stroke. Such pulses have been found to occur in groups at the initiation of a lightning strike to an aircraft and randomly throughout the lightning flash duration, together with the other current components (Figure 7-3). While not likely to cause physical damage to the aircraft, the random and repetitive nature of these pulses may cause interference or upset to certain systems. The recommended waveform set comprises repetitive component H waveforms in three bursts of 20 pulses each as shown in Figure 9-15. The minimum time between induced Component H pulses within a burst is 50μs and the maximum is 1,000μs.

The 3 bursts are distributed according to the following constraints:

- the minimum time between bursts is 30 ms,

- the maximum time between bursts is 300 ms.

If the maximum times between individual pulses and bursts were assumed, the Multiple Burst Waveform set would occupy 0.62 seconds.

Waveform H can be mathematically described by using the following formula:

$$i = I_0\left(e^{-\alpha t} - e^{-\beta t}\right)$$

where:

$I_0 = 10{,}572$ A
$\alpha = 187{,}191$ s^{-1}
$\beta = 19{,}105{,}100$ s^{-1}
t is time (s)

Component H is presented in Figure 9-16(a).

The frequency content of component H is given on Figure 9-16(b).

> The primary purpose of the Multiple Burst Waveform set is to evaluate system functional upset of systems that may be susceptible to effects of multiple induced transients. It is not necessary that this waveform set be applied at the defined levels in a test. Instead, the internal environment due to a single component H Waveform may be determined by analysis or test and the Multiple Burst combination of induced transients applied to the system/equipment.

The Multiple Burst Waveform set is used only for indirect effects evaluation.

50μs ≤ Δt ≤ 1000μs

10kA

H H H H
1 2 3 20

One burst is composed of 20 pulses.
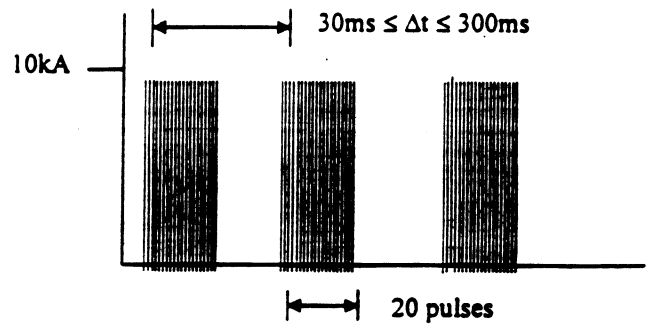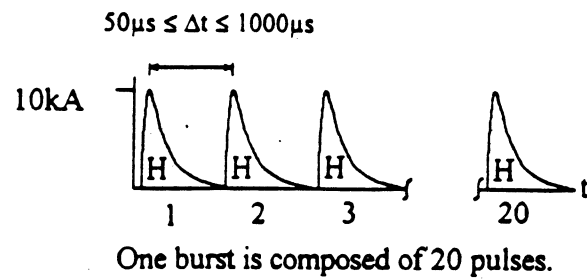
10kA

30ms ≤ Δt ≤ 300ms

t

20 pulses

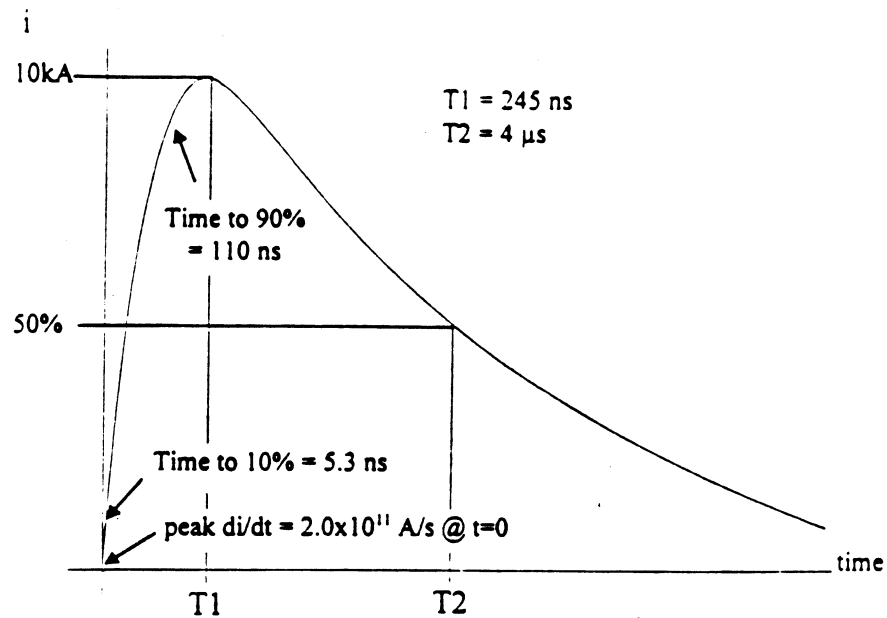Figure 9-15. Multiple Burst Waveform set.

Figure 9-16(a). Current component H for analysis purposes and indirect effects. test purposes
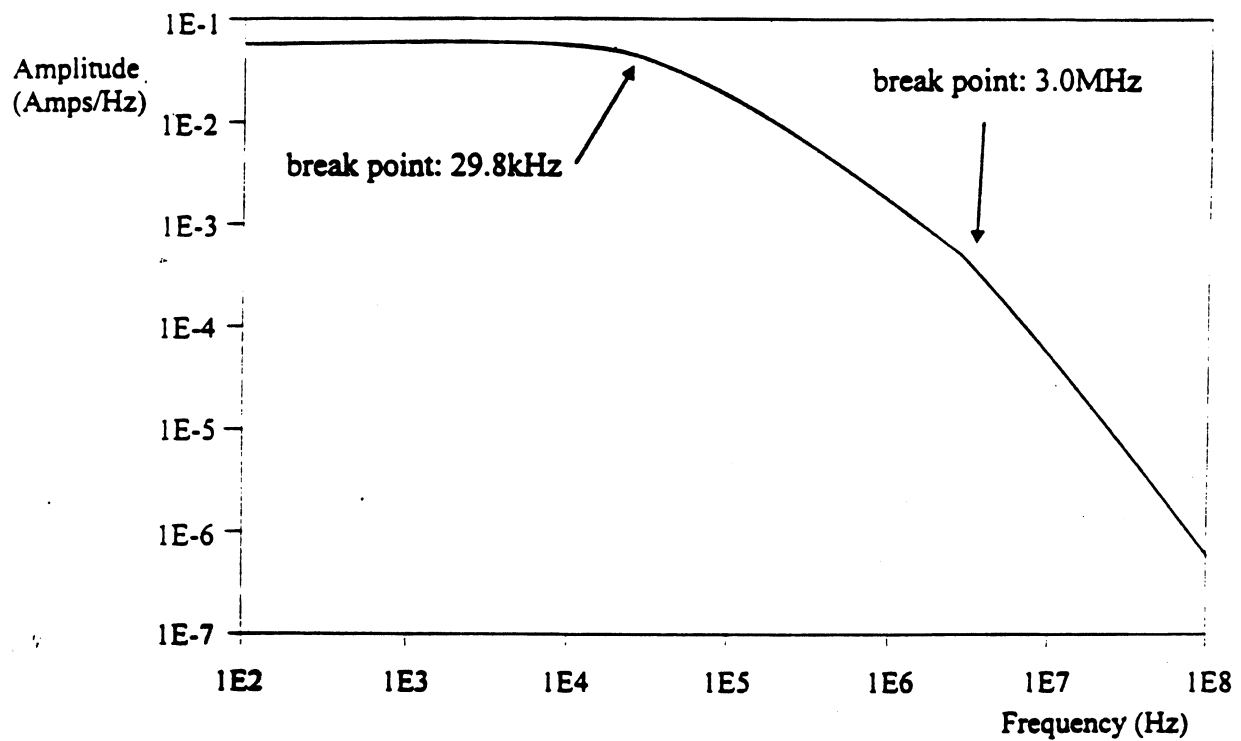

Figure 9-16(b). --   Frequency content (amplitude spectrum) of current component H

9.4 Application of the Idealized External Environment Waveforms/Components to Aircraft Testing

The application of the lightning environment waveforms and components to specific zones as described in reference 4.1 is shown in Table 9-1.

Table 9-1: Application of Lightning Environment to Aircraft Zones

Aircraft Zone	Voltage Waveforms(s)	Current Component(s)
1A	A, B, D	A, B, C*, H
1B	A, B, D	A, B, C, D, H
1C	A	A_h, B, C*, D, H
2A	A	D, B, C*, H
2B	A	D, B, C, H
3		A, B, C, D, H
Lightning Strike Model Tests	C	

Subsets of these waveforms are to be used for direct and indirect effect evaluation. Waveforms appropriate for direct effects include voltage Waveforms A, B, C, D, and current Components A, A_h, B, C, and D.

Waveforms appropriate for indirect effects evaluation include current components A, D, and H which are individual components of the single stroke, MS and MB Waveform sets.

Since most of an airframe is located within Zone 3, the single stoke, MS and MB Waveform sets are nearly always applicable. However, there may be special cases in Zone 2 where the aircraft system or subsystem and its wiring are isolated from the effects of the initial A current component and current component D is more applicable for single stroke evaluation. In addition there may be situations where a system (i.e. equipment and associated wiring) is located solely within one area of the aircraft (e.g. a nose equipment bay), this system may not be exposed to all of the strokes of the magnitude at those defined by the MS waveform set.

The uses of these waveforms are described in detail in References 4.2, 4.4 and 4.7.

10.0 IDEALIZED STANDARD INDUCED TRANSIENT WAVEFORMS

10.1 General

The idealized transient waveforms presented in this section are intended for design and verification of adequate lightning indirect effects protection of systems and equipment by analysis and/or test.

The external lightning environment will interact with an aircraft to induce voltage and current transients in conductors such as wiring inside the aircraft.

The high amplitudes and rates of change of Components A, D, and H (paragraphs. 9.3.1, 9.3.6, and 9.3.8, respectively) produce the major induced transients in aircraft wiring. Components B and C do not induce significant transients.

There are several mechanisms by which the external environment induces transients. These can be broadly divided into aperture coupling and resistive coupling. Most actual induced transients are complex waveforms that result from combinations of both coupling mechanisms. For design and verification purposes it has proved most practical to separate them and define a set of simpler waveforms described below. Typical TCLs or ETDLs associated with these waveforms are provided in Section 10.6.

10.2 Aperture Coupling

Magnetic fields penetrating through apertures will induce:

i. Current(s) whose waveshape is that of the driving external environment Waveform A (Waveform 1, Figure 10-1) in conductors or shields terminated to structure through low impedance's at each end.

ii. Voltage whose waveshape is that of the derivative of the driving external environment Waveform A (Waveform 2, Figure 10-2) in loops existing between cables and the structure.

Electric and/or magnetic fields penetrating through apertures will drive or excite resonance's on cables producing oscillatory currents and voltages which have the form of damped sinusoids (Waveform 3, Figure 10-3). The frequency will be dependent on the structure length, and/or cable length and terminating components. Frequencies often range between 1 MHz and 10 MHz; other frequencies outside this range have also sometimes been observed.

10.3 Structural IR Voltage and Diffusion Flux Coupling

These mechanisms will produce voltages in loops existing between cables and the structure, which are the sum of the structural IR voltage between the end points of the cables and the voltage resulting from fields diffused through the structural materials. These voltages may have the shape of the external environment Waveform A for resistive structures or slower double exponential waveshapes for highly conductive structures.

amplitude of eighth half cycle shall be at least 25% but not more than 75% of the second half cycle when injecting into a 100 ohm load.

8ᵗʰ half cycle

2ⁿᵈ half cycle

Frequency of resonances may range from 1MHz to 50MHz.
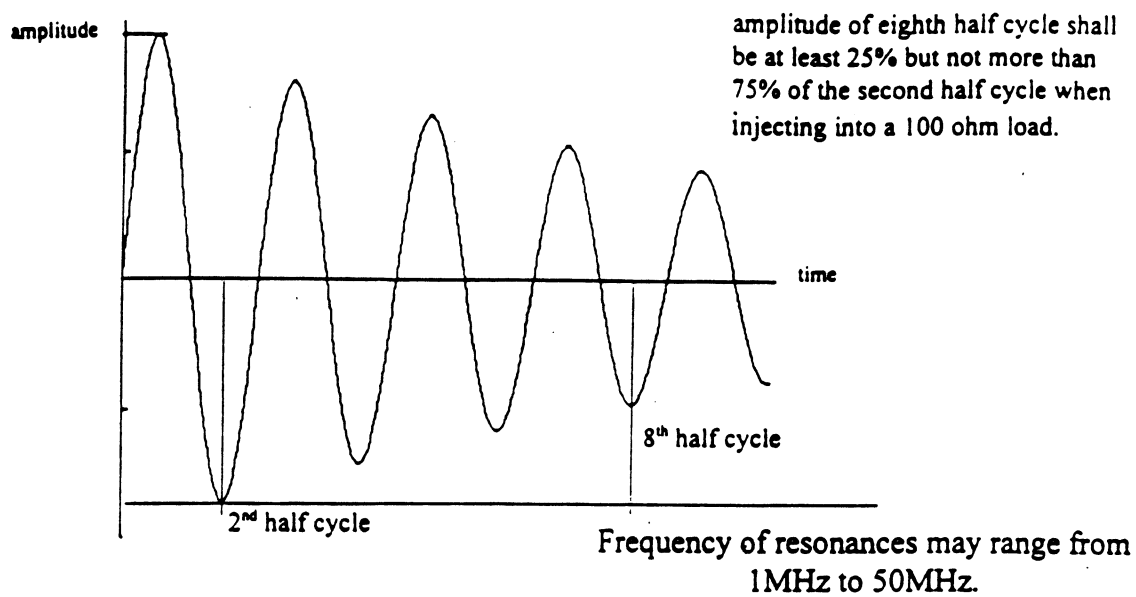
Figure 10-3. Damped sinusoidal voltage/current Waveform 3.

$T1 = 6.4 \ \mu s \pm 20\%$.
$T2 = 69 \ \mu s \pm 20\%$

Time to 90% = 3.0 μs

50%

Time to 10% = 0.15 μs

T1

T2

time
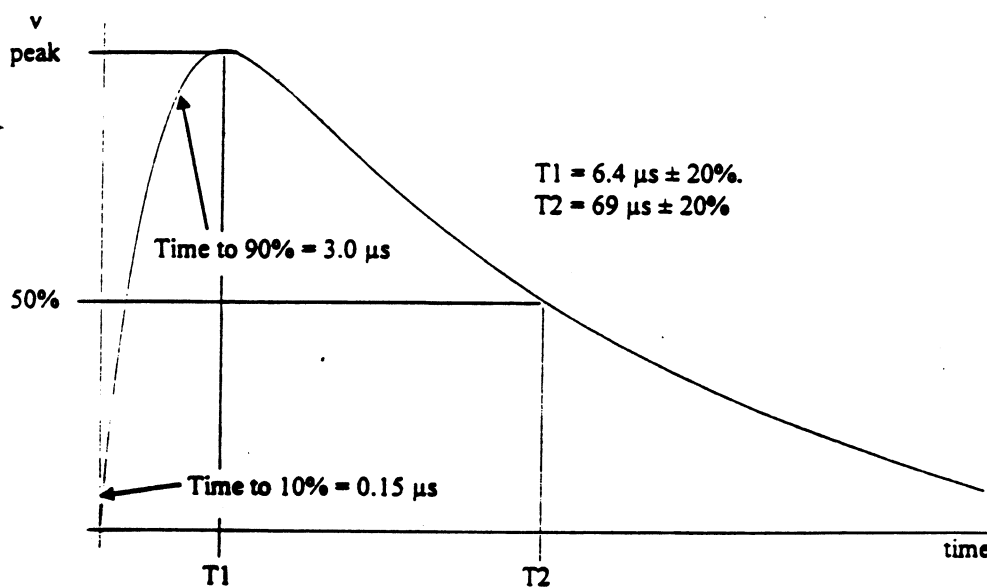
Figure 10-4. Double exponential voltage Waveform 4.
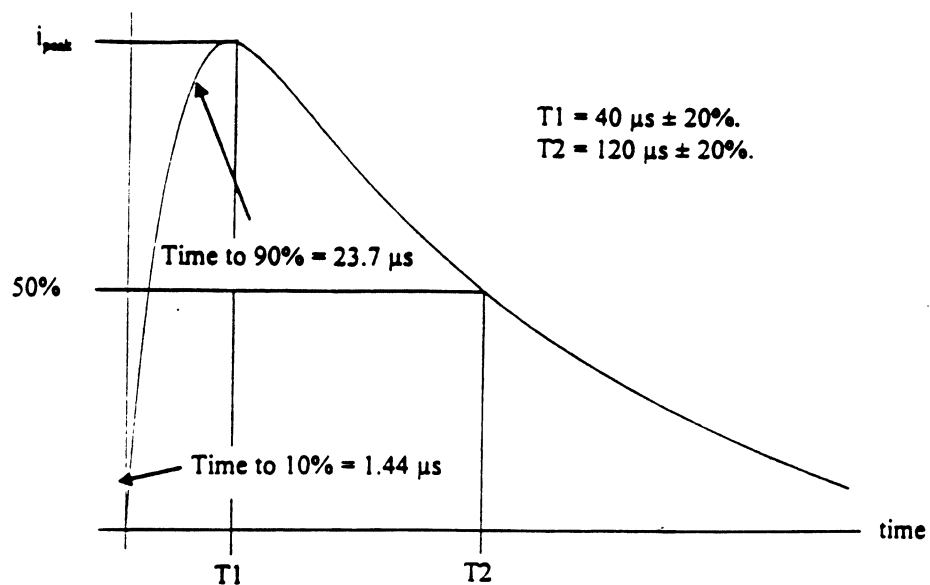
Figure 10-5. Double exponential current Waveform 5A.

T1 = 40 μs ± 20%.
T2 = 120 μs ± 20%.

Time to 90% = 23.7 μs

Time to 10% = 1.44 μs
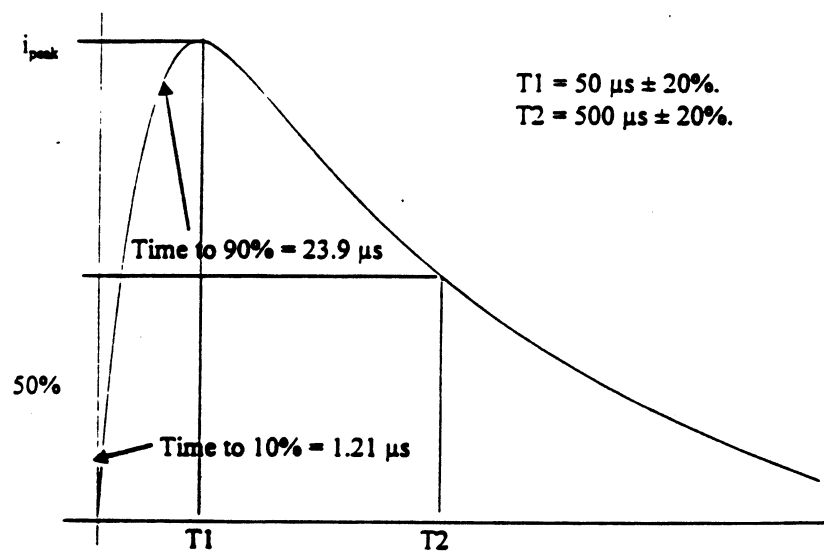
Figure 10-6. Double exponential current Waveform 5B.

T1 = 50 μs ± 20%.
T2 = 500 μs ± 20%.

Time to 90% = 23.9 μs

Time to 10% = 1.21 μs

10.5 Multiple Burst

Transient responses arising from component H of the Multiple burst Waveform set will also occur in the Multiple Burst sequence. The predominant waveform responses are voltage Waveform 3_H in a frequency range between 1 MHz and 10 MHz or a current waveform (Waveform 6_H) which has the same shape as the external environment component H. In this latter case, for test purposes, the component H rise time can be effectively produced with a current Waveform 3_H at a frequency of 5 MHz or higher. Equipment and system test levels for voltage Waveform 3_H typically have an amplitude of 60 percent of the component A Waveform 3 voltage response. Current Waveform 3_H typically has an amplitude of $1/20^{th}$ of the component A Waveform 3 current response. Equipment and systems test levels for Waveform 6_H would typically have a maximum level of $1/20^{th}$ of the component A Waveform 1 response.
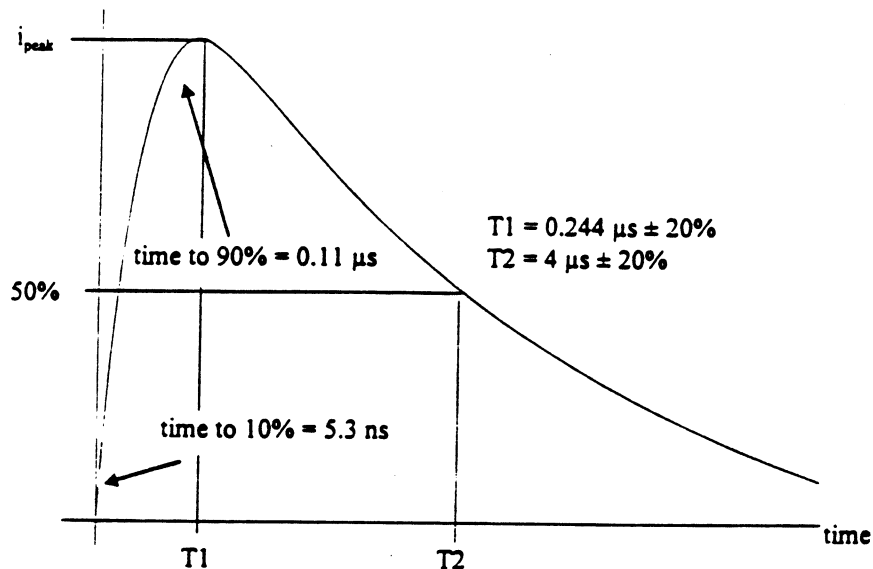
Figure 10-7. Double exponential current Waveform 6.

10.6 Typical Transient Amplitudes

The amplitudes of induced voltages in individual conductors and cable bundles encountered in a wide variety of aircraft installations have ranged from less than 50 volts to 3200 volts. The amplitudes of typical induced currents have ranged from less than 20 amperes to 1600 amperes in individual conductors and from less than 20 amperes to 5000 amperes in typical cable bundles.

This broad range has been subdivided into five narrower ranges that correspond roughly to aircraft electromagnetic regions that have been or can be achieved through design measures. Since the various transient waveforms arise from different coupling mechanisms, it follows that regions in an airframe designed to meet a particular level for one waveform will not necessarily meet the same level for the other transient waveforms.

Descriptions of five voltage and current amplitude levels and the aircraft areas with which they can be associated are provided in References 4.3 and 4.5. These levels are shown in Table 10-2 for individual conductors and Table 10-3 for cable bundle single and Multiple Stroke amplitudes, and Table 10-4 for cable Multiple Burst amplitudes.

Table 10-2.: Individual Conductor TCL, ETDL or Test Levels due to Current component A.

Level	Waveforms		
	3	4	5
	V/I	V/I	V/I
1	100/4	50/10	50/50
2	250/10	125/25	125/125
3	600/24	300/60	300/300
4	1500/60	750/150	750/750
5	3200/128	1600/320	1600/1600

Table 10-3.: Cable Bundle TCL, ETDL or Test Levels due to Current component A.

Level	Waveforms				
	1	2	3	4	5
	V/I	V/I	V/I	V/I	V/I
1	50/100	50/100	100/20	50/100	50/150
2	125/250	125/250	250/50	125/250	125/400
3	300/600	300/600	600/120	300/600	300/1000
4	750/1500	750/1500	1500/300	750/1500	750/2000
5	1600/3200	1600/3200	3200/640	1600/3200	1600/5000

Table 10-4. Cable Bundle TCL, ETDL or MB Test Levels due to Current Component H.

Level	Waveforms	
	3_H	6_H
	V/I	I
1	60/1	5
2	150/2.5	12.5
3	360/6	30
4	900/15	75
5	1920/32	160

11.0 SUMMARY OF WAVEFORMS/WAVEFORM SETS

A summary of the characteristics of the external lightning current components and the parameters necessary for their double exponential descriptions is presented in Table 11-1.

A summary of the characteristics of the induced transient waveforms and the parameters necessary for their double exponential descriptions is presented in Table 11-2.

Table 11-1. Summary of idealized external lightning current component parameters.

Parameter	Current component						
	A	A_h	B	C	D	D/2[1]	II[2]
I_0 (A)	218,810	164,903	11,300	400	109,405	54,703	10,572
$\alpha(s^{-1})$	11,354	16,065	700	N/A	22,708	22,708	187,191
$\beta(s^{-1})$	647,265	858,888	2,000	N/A	22,708	22,708	187,191
ipeak (A)	200,000	150,000	4,173	400	1,294,530	1,294,530	19,105,100
di/dt_{max} (A/s) (t=0+ s)	1.4×10^{11}	1.4×10^{11}	N/A	N/A	100,000	50,000	10,000
di/dt (A/s)	1.0×10^{11} (t=0.5 µs)	1.0×10^{11} (t=0.375 µs)	N/A	N/A.	1.4×10^{11}	0.7×10^{11}	2.0×10^{11}
action integral (A^2s)	2.0×10^6	0.8×10^6	N/A	N/A	1.0×10^{11} (t=0.25 µs)	0.50×10^{11} (t=0.25 µs)	N/A
					0.25×10^6	0.0625×10^6	N/A

1) Applicable for the Multiple Stroke

2) Applicable for the Multiple Burst

Table 11-2. Summary of induced transient Waveform parameters.

PARAMETER	WAVEFORM							
	1	2	3	4	5A	5B	3H	6H
Pin tests	V/I	V/I	V/I	V/I	V/I	V/I	V/I	V/I
Level 1 V_0/I_0	50/100	N/A	100/4	50/10	50/50	50/50	N/A	N/A
Level 2 V_0/I_0	125/250	N/A	250/10	125/25	125/125	125/125	N/A	N/A
Level 3 V_0/I_0	300/600	N/A	600/24	300/60	300/300	300/300	N/A	N/A
Level 4 V_0/I_0	750/1500	N/A	1500/60	750/150	750/750	750/750	N/A	N/A
Level 5 V_0/I_0	1600/3200	N/A	3200/128	1600/320	1600/1600	1600/1600	N/A	N/A
Cable tests								
Level 1 V_0/I_0	50/100	50/100	100/20	50/100	50/150	50/150	60/1	5
Level 2 V_0/I_0	125/250	125/250	250/50	125/250	125/400	125/400	150/2.5	12.5
Level 3 V_0/I_0	300/600	300/600	600/120	300/600	300/1000	300/1000	360/6	30
Level 4 V_0/I_0	750/1500	750/1500	1500/300	750/1500	750/2000	750/2000	900/15	75
Level 5 V_0/I_0	1600/3200	1600/3200	3200/640	1600/3200	1600/5000	1600/5000	1920/32	160
α (s^{-1})	11,354	11,354	$0.231f$[4]	11,354	12,632	1585	$0.231f$[4]	187,191
β (s^{-1})	647,265	647,265	N/A	647,265	43,605	80,022	N/A	19,105,100
ω (Rad.s^{-1})	N/A	N/A	$2\pi f$[4]	N/A	N/A	N/A	$2\pi f$[4]	N/A
Equation	DE[1]	Deriv[2]	DS[3]	DE[1]	DE[1]	DE[1]	DS[3]	DE[1]
Peak Multiplier[5]	1.094	1.00	1.059	1.094	2.334	1.104	1.059	1.057

Notes:

1) DE: Double exponential of the form $v_t = V_0 (e^{-\beta t} - e^{-\alpha t})$ or $i_t = I_0 (e^{-\beta t} - e^{-\alpha t})$

2) Deriv: Derivative of a double exponential of the form $v_t = \beta e^{-\beta t} - \alpha e^{-\alpha t}$ or $i_t = \beta e^{-\beta t} - \alpha e^{-\alpha t}$

3) DS: Damped sinusoid of the form $v_t = V_0 \sin(\omega t) e^{-\alpha t}$ or $i_t = I_0 \sin(\omega t) e^{-\alpha t}$

4) f: Frequency in Hertz

5) The value of the peak multiplier is that which when multiplied by the peak threat level given above provides a value for V_0 or I_0

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